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# Industrial Hemp Finola Variety Photosynthetic, Morphometric, Biomechanical, and Yield Responses to K Fertilization Across Different Growth Stages

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**Abstract:** The growing interest in *Cannabis sativa* as a highly used crop is present worldwide. There are limited data about the effect of potassium (K) fertilizer on industrial hemp yield for dual purposes (seed and stem production). The current study aimed to investigate the influence of adding two different K fertilizers, KCl and $K_2SO_4$, at two growth stages (flowering and ripening) on the productivity and chlorophyll *a* fluorescence (ChlF) of *Cannabis sativa,* variety Finola. Before sowing, different K treatments were applied: $K_1$—100 kg ha$^{-1}$ KCl (60% K) and $K_2$—100 kg ha$^{-1}$ $K_2SO_4$ (52% K, S 17%). The OJIP (O stands for "origin" (minimal fluorescence), P for "peak" (maximum fluorescence), and J and I for inflection points between the O and P levels) data were recorded and used for ChlF transients and individual ChlF parameters during vegetation. At harvest, the stem morphology parameters and yield (plant height, stem weight and diameter, and stem and seed yield), tensile strength, and the modulus of elasticity were determined. The results show the sensitivity of minimal ($F_0$) and maximal fluorescence ($F_m$), electron transport from $Q_A$ to intersystem electron acceptors ($ET_0/(TR_0 - ET_0)$), and electron transport flux until PSI acceptors ($RE_0/RC$) to K fertilization. The parameters that described electron transport ($ET_0/RC$, $\psi E_0$, and $\varphi E_0$), performance index on absorption basis ($PI_{ABS}$, $TR_0/DI_0$, and $\varphi P_0$), dissipation ($DI_0/RC$), and electron transport to photosystem I ($\varphi R_0$ and $\delta R_0/(1 - \delta R_0)$) had a reaction only at the growth stage, indicating a change in their activity during the aging of the *Cannabis sativa* plants. The average stem height was 67.5 cm, and the stem diameter was 0.41 cm. The different K sources did not significantly influence the stem height and diameter, nor the dry stem (on average 12.2 t ha$^{-1}$) and seed yield (on average 1.85 t ha$^{-1}$). The tensile strength of individual hemp stems was the highest with $K_2SO_4$ (53.32 MPa) and the lowest with KCl (49.25 MPa). The stem stiffness by modulus of elasticity was about 5 GPa on average for all the treatments. In general, the photosynthetic parameters in this study varied more between the growth stages than between the different K fertilizer formulations. Moreover, based on the results of this study, it can be recommended to use both fertilizers, KCl and $K_2SO_4$, in dual-purpose industrial hemp production since no significant effect was found for the stem morphometric and biomechanical parameters as well as for the agronomic parameters.



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## 1. Introduction

Industrial hemp is considered one of the oldest non-food crops used for fiber production [1–3]. The large hemp producers globally are Chile, France, the USA, and Canada. In Europe, in 2022, the areas with industrial hemp cultivation for seed production totaled around 8600 ha and for raw hemp stem, around 37,000 [4]. France is the largest producer, accounting for more than 60% of EU production, followed by Germany (17%), and the Netherlands (5%) [5]. Industrial hemp cultivation and processing were very popular during the 20th century, especially in Eastern Croatia, in the Slavonia and Baranja areas, and in Serbia, in the Vojvodina area [6,7]. Around 1000 ha is sown in Croatia, mainly for the purpose of seed production [8].

Unlike other crops, industrial hemp is somewhat controversial because some varieties of *Cannabis* genera are grown in a specific way and used to obtain psychoactive substances, which is prohibited by the law. The plant contains cannabinoids, of which Δ9-tetrahydrocannabinol (THC) is the most important. Thus, nowadays, renewed interest in industrial hemp cultivation is subject to certain regulations. The permitted THC content for industrial hemp varies from country to country. Due to the THC content, special regulations are in force, which mandate that the variety of industrial hemp being cultivated must have a THC content below 0.3% in Europe for hemp crops used for industrial purposes [9]. In the UK, the maximum content is up to 0.2% THC, and in New Zealand, it can vary from 0.35% to 0.50% [9]. According to Kaur et al. [10], a higher content is allowed in Australia and Mexico (1.0%), Malaysia (0.5%), and Canada (0.3%). In Croatia, the regulation [11] mandates that industrial hemp can be cultivated for food production if the THC content does not exceed 0.2%.

A major advantage of the increased interest in the re-cultivation of industrial hemp in Eastern Croatia is the change in the regulations, which now allow the use of whole plants, not just seeds [11,12]. These regulations offered an advantage that opened up many opportunities for the use and processing of stems and other plant parts not only for the food industry [13–15] but also in medicine, as an environmentally friendly material in numerous other processing branches, and as a raw material for bioethanol production [16–21]. Industrial hemp has a wide range of applications in sectors such as the automotive, paper, and textile industries, etc. Its seeds are rich in oil (25–38%), proteins (18–23%) [22], and essential fatty acids, with a high ratio of polyunsaturated to saturated fatty acids [23–25]. Industrial hemp has great potential as a renewable and environmentally friendly building material [26,27].

Macronutrients (N—nitrogen, P—phosphorus, K—potassium) are of great importance for field crops and are usually added to the soil [28–31]. A positive response of industrial hemp to nitrogen fertilization has been previously recognized, not only for biomass production but also for increased seed yield and plant height [32–34]. However, Struik et al. [35] reported that a relatively small amount of nitrogen is sufficient to meet the plants' nitrogen requirements. Research on P and K fertilization in industrial hemp is still limited. Ahmadi et al. [36] reported that P increases plant height, directly influencing plant biomass production and improving flowering. For industrial hemp cultivation, K is important for prolonging the flowering of male plants [37]. Zehler et al. [38] stated that K often depends on how it is combined in the fertilizer, which may influence crop yield and quality.

The most common formulation of K fertilizers is potassium chloride (KCl), followed by potassium sulfate ($K_2SO_4$). Even though chloride is an essential element, it can be used in small quantities, similarly to micronutrients. It is involved in osmosis and ionic balance within the cell [39]. Sulphate is a major plant nutrient since it is a component of proteins [40]. Both $Cl^-$ and $SO_4{}^{2-}$ regulate plant water uptake, but Cl is more hydrated and, therefore, has a greater swelling effect than $SO_4{}^{2-}$. Cl reduces transpiration, increases stomatal opening, and increases water uptake by the plants [38].

Very few studies have been published that have examined the yield of industrial hemp stem and seed in relation to photosynthetic activity parameters. As a short-day plant, hemp requires a photoperiod of 12–14 h of daylight [36]. Zehler et al. [38] reported that in higher doses of Cl, photosynthetic activity is lower due to lowered chlorophyll content, and on the contrary, $SO_4{}^{2-}$ in plants is concerned with chlorophyll synthesis.

Recently, the importance of stem and leaf mechanobiology has accelerated, not only due to harvest and processing but also in breeding programs and crop loss due to logging and stem deformation [41]. The tensile strength and stem stiffness are closely connected to plant species, stalk diameter, maturity, stem moisture, and cellulase content [42–44]. Due to their tensile strength and stiffness, industrial hemp fibers and stems can be used as reinforcements for composite materials. Liu et al. [45] investigated the influence of the industrial hemp plant's growth stage. However, research on the influence of K fertilizer treatment on the stiffness and tensile strength of industrial hemp stems is limited.

The cultivar Finola, which is used in this research, originates from Finland and is dioecious and auto-flowering. Lančaričová et al. [24] indicate that Finola needs fewer than 100 days to reach the maturity stage, and its buds contain low levels (<0.2%) of THC. The authors stated that it was the first cultivar registered as an oilseed crop in Europe. In Croatia, the Finola cultivar is the most common variety nowadays, mostly for seed production. Still, the potential of Finola utilization is not fully recognized. In Croatia, stem use was forbidden until 2019 [12] (OG 39/2019).

The aim of this study was to evaluate the dual-purpose production yield (stalk and seed yield) of industrial hemp of the Finola variety in eastern Croatia. In addition, since there are limited data on the influence of K fertilization on industrial hemp Finola cultivar yield production, the effect of the most common K fertilizers (KCl or $K_2SO_4$) on photosynthetic activity during growth and stem mechanobiology (stiffness and tensile strength), morphology parameters, and finally on the stem and seed yield was determined.

## 2. Materials and Methods

### *2.1. Field Trial*

The field trial was conducted at the Tenja location in Eastern Croatia. The pre-crop was an opium poppy, and the basic cultivation was carried out to a depth of 25–30 cm during November 2020. In the spring of 2022, the winter furrow was closed, after which further supplementary soil cultivation was started to create an optimal seeding layer. Fertilizer was applied before sowing to avoid leaching of the $Cl^-$ and $SO_4{}^{2-}$ ions in the winter period. Presowing fertilization was conducted with different K fertilizers such as $K_0$—without presowing fertilization (control treatment), $K_1$—100 kg ha$^{-1}$ KCl (60% K), and $K_2$—100 kg ha$^{-1}$ $K_2SO_4$ (52% K, S 17%). Other macronutrients were not added to exclude their influence on the obtained results.

For this study, the Finola variety was sown on 17 April 2022 in three replications in a randomized block design. A pneumatic seed drill was used for the industrial hemp sowing at an inter-row distance of 25 cm and a depth of 3 cm. The sowing rate was 30 kg ha$^{-1}$.

All weeds were manually removed from the field approximately every ten days. Even though the experiment was set up using non-organic practices, no agrochemicals were used since there were no important pests or disease attacks, and there was no need for pesticide application.

### 2.2. Weather Data

At the time of sowing in April, according to the Croatian Meteorological and Hydrological Service [46], according to the distribution of percentiles, the temperature conditions in Osijek for April were described as cold (Figure 1), but the industrial hemp germination was satisfied. During May, there were no major deviations in temperature and precipitation. June 2022 was extremely warm throughout Croatia, and for the Osijek area, the average temperature in June was 3.2 °C lower than the long-term mean, while the amount of precipitation was average. The average air temperature in July 2022 was 1.8 °C higher as compared to the long term mean 1981–2010 for the Osijek area, with a lack of precipitation. Such weather conditions during the summer months have an unfavorable effect on the growth of industrial hemp, and the plant relatively quickly went into the flowering stage (generative stage).

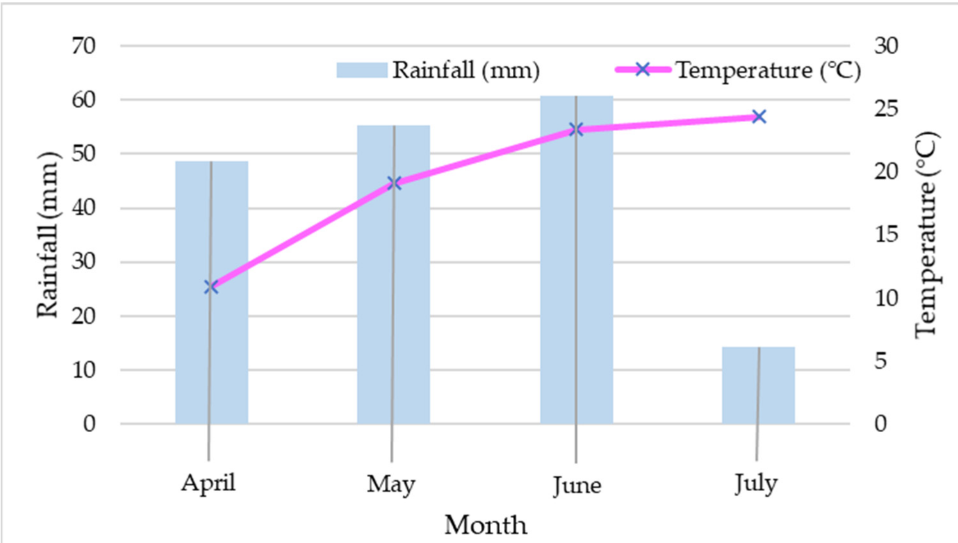



**Figure 1.** Weather data for industrial hemp during the 2022 vegetation period (Osijek location).

### 2.3. Measurements of Photosynthetic Activity and Chlorophyll Content

The fluorescence was analyzed using a portable chlorophyll fluorescence instrument, Handy PEA (Hansatech Instruments Ltd., King's Lynn, UK). Chlorophyll *a* fluorescence was assessed on the adaxial surface of the leaves at the base of the inflorescence of the main stem (fully grown leaf) of the *Cannabis* plant (Figure 2), subjecting the plants to a period of 30 min of darkness before measurement [47]. All measurements were conducted in the morning, between 7:00 and 8:00 a.m. Photosynthetic activity was determined in two plant growth stages, according to Mediavilla et al. [48]. The first measurement was on 5 July in the flowering stage, code 2202 (50% of bracts formed), and the second measurement was on 15 July in the seed maturity stage—ripening stage, code 2204 (50% of the seeds were hard). From each fertilization treatment, 10 plants were measured, and a total of 60 plants were measured in every growth stage. ChlF was measured after applying a saturating light pulse > 3500 μmol $m^{-2}$ $s^{-1}$ for one second (s). The ChlF parameters (Table 1) were calculated following the methodology described by Strasser et al. [49] and Yusuf et al. [50]. Specific events of OJIP transient in the OK, OJ, JI, OI, JI, and IP phases were calculated and presented as different $\Delta V_{OP}$, $\Delta V_{OK}$ (L band), $\Delta V_{OJ}$ (K band), $\Delta V_{OI}$ (J band), $\Delta V_{JI}$ (H and I bands), and $\Delta V_{IP}$ (G band) normalized to the controls (K0 treatment) per growth stage [50].

**Figure 2.** Photosynthetic activity measurements and leaf clip position for industrial hemp.

**Table 1.** List of chlorophyll *a* fluorescence parameter used in the analyses.

| Parameter Label | Description of Chlorophyll *a* Fluorescence Parameters |
|---|---|
| $F_0$ | Minimal fluorescence yield of the dark-adapted state |
| $F_m$ | Maximal fluorescence yield of the dark-adapted state |
| ABS/RC | Absorption flux per active reaction center (RC) |
| $DI_0/RC$ | Dissipation flux per active RC |
| $TR_0/RC$ | Trapping flux per active RC |
| $ET_0/RC$ | Electron transport flux per active RC |
| $RE_0/RC$ | Electron flux reducing terminal electron acceptors at the photosystem I (PSI) acceptor side per RC |
| $\varphi P_0$ | Maximal photochemical quantum yield |
| $\psi E_0$ | The probability that a trapped exciton moves an electron into the electron transport chain beyond $Q_A$ |
| $\varphi E_0$ | Quantum yield for electron transport |
| $\delta R_0$ | The probability that an electron is transported from reduced PQ to the electron acceptor side of PSI |
| $\varphi R_0$ | The quantum yield of electron transport from $Q_A^-$ to the PSI end electron acceptors |
| RC/ABS | Density of RC on chlorophyll *a* basis |
| $TR_0/DI_0$ | Flux ratio trapping per dissipation |
| $ET_0/(TR_0 - ET_0)$ | Electron transport from $Q_A^-$ to intersystem electron acceptors |
| $PI_{ABS}$ | Performance index on absorption basis |
| $\delta R_0/(1\text{-}\delta R_0)$ | Electron transport from $PQH_2$ to final PSI acceptors |
| $PI_{TOTAL}$ | Performance index for energy conservation from exciton to the reduction in PSI terminal acceptors |

Leaf chlorophyll content was determined with a chlorophyll content meter, model CL-01 (Hansatech Instruments, Pentney, UK).

### *2.4. Stem and Seed Harvest and Post-Harvest Measurements*

The harvest was conducted on 26 July 2022. Whole plants were harvested by hand from each fertilization treatment and replicated from $2m^2$ in three replications. At that time, the stem of the female plants was still green and inseminated. Female industrial hemp plants were light green to golden brown. Before harvesting the plants, the number of plants per unit area was determined, and then the proportion of male and female plants was determined. After the harvest, the yield (t $ha^{-1}$) of the industrial hemp stem (fresh and air-dried stems) and seed yield (t $ha^{-1}$) was determined. The plants were dried, and after that, the stem diameter was determined.

From each treatment, ten individual plants were taken for measuring of the morphometric parameters. Stem height (cm) was measured with a ruler, representing the height of the whole plant, including the inflorescence. Stem diameter (cm) was determined by measuring 2 cm above and beyond each nodule measured with digital vernier calipers. The stem diameter represents the average of all measurements of the stem.

### 2.5. Macronutrient Stem Status

The stem for macronutrient status analysis was dried to a constant mass at 105 °C. After drying, the stems were milled in the laboratory mill (Retsch SM 100, Haan, Germany). This study determined three macronutrients: N, P, and K. A C/N analyzer was used to determine the N, P, and K macronutrient status after digestion with sulfuric acid and hydrogen peroxide and afterward was determined with AAS spectrometry for K. The P was determined using photometry at room temperature at wavelength 400 nm.

### 2.6. Tensile Testing of Industrial Hemp Stems

Stem tensile tests were conducted to determine the effects of the two types of K fertilizers, KCl and $K_2SO_4$, on stem tensile strength and stiffness. The impact of fertilization on hemp stems has been compared to stems that have not been fertilized. Three sets of three industrial hemp samples were prepared for testing. The center part of the industrial hemp stem, which was bounded by the nodes, was chosen for the stem samples. The first group of samples was steamed without presowing fertilization ($K_0$); the second group of samples was fertilized with potassium chloride (KCl, $K_1$); and the third group of samples received 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 K fertilization: $K_0$, $K_1$, and $K_2$. The third mark, z, indicates the number of samples, which can range from one to three for each group of samples. The tests were conducted on stems with a complete cross-section. Before the test, the sample's length, external diameters at three points (ends and middle), and straw wall thickness (ends) were measured, and the average cross-sectional areas were calculated.

The sample was loaded under uniaxial tension using the Zwick/Roell Z600 material testing device (Ulm, Germany) to determine the maximum breaking force for the hemp stems. TestXpert II software was used for both the test management and data registration. 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. Figure 3 shows the test setup. The tension in the samples was achieved by controlling the displacement of a moving crosshead at a test speed of 0.5 mm/min. Testing is considered finished when the tensile strength drops to 80%. The moving crosshead's axial forces and displacements were measured and recorded during the test. The stresses and strains in the specimen were calculated using the measured forces and displacements.

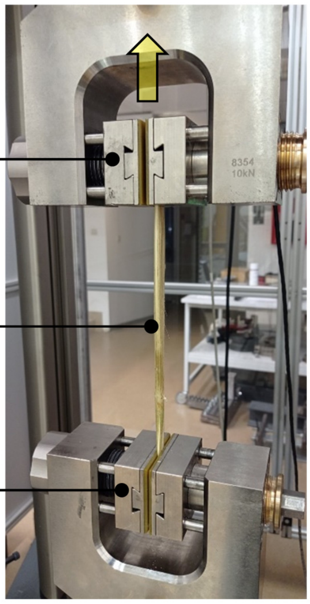



**Figure 3.** The tensile test setup of industrial hemp stem.

## *2.7. Statistical Analysis*

The influence of different K treatments was tested with ANOVA in SAS Enterprise Guide 7.1. Differences between the means were shown at the $p < 0.05$ probability level. Mean values and standard deviations of ChlF parameters (relative units) are shown in Table 2. A factorial ANOVA for the ChlF parameters ($n = 60$) was used to determine the statistical differences between the fertilization treatments ($K_0$, $K_1$, and $K_2$) and the developmental stage (flowering and ripening) of the industrial hemp plants. Factorial ANOVA was followed by the Tukey post hoc honestly significant difference (HSD) test at $p < 0.05$. Correlation analysis was conducted for the stem morphometric parameters, seed and stem yield, stem stiffness and tensile strength, and macronutrient status in the stem dry matter. Pearson's coefficient of correlation was used to determine the correlations.

**Table 2.** Chlorophyll *a* fluorescence (ChlF) parameters for KCl and $K_2SO_4$ fertilization treatments in the flowering and ripening stage of *Cannabis* plants.

| * ChlF Parameters | Flowering Stage | | | Ripening Stage | | | HSD | HSD | HSD |
|---|---|---|---|---|---|---|---|---|---|
| | Control ($K_0$) | KCl | $K_2SO_4$ | Control | KCl | $K_2SO_4$ | GS | FT | GS × FT |
| $F_0$ | 598 ± 58 | 600 ± 51 | 624 ± 26 | 658 ± 110 | 501 ± 45 | 596 ± 77 | ns | 42.50 | 60.11 |
| $F_m$ | 3958 ± 93 | 4021 ± 54 | 4036 ± 137 | 3811 ± 288 | 3081 ± 472 | 3554 ± 503 | 162.33 | 198.81 | 281.17 |
| ABS/RC | 2.103 ± 0.183 | 2.114 ± 0.269 | 2.136 ± 0.169 | 2.239 ± 0.228 | 1.926 ± 0.209 | 2.198 ± 0.369 | ns | ns | ns |
| $DI_0$/RC | 0.318 ± 0.045 | 0.318 ± 0.066 | 0.332 ± 0.044 | 0.389 ± 0.083 | 0.318 ± 0.054 | 0.381 ± 0.132 | 0.04 | ns | ns |
| $TR_0$/RC | 1.784 ± 0.147 | 1.796 ± 0.204 | 1.804 ± 0.127 | 1.850 ± 0.163 | 1.608 ± 0.163 | 1.817 ± 0.252 | ns | ns | ns |
| $ET_0$/RC | 0.964 ± 0.055 | 0.945 ± 0.049 | 0.928 ± 0.038 | 0.803 ± 0.081 | 0.780 ± 0.059 | 0.778 ± 0.033 | 0.03 | ns | ns |
| $RE_0$/RC | 0.395 ± 0.068 | 0.335 ± 0.083 | 0.321 ± 0.057 | 0.350 ± 0.064 | 0.341 ± 0.041 | 0.322 ± 0.049 | ns | 0.04 | ns |
| $\varphi P_0$ | 0.849 ± 0.012 | 0.851 ± 0.012 | 0.845 ± 0.009 | 0.828 ± 0.023 | 0.836 ± 0.015 | 0.830 ± 0.029 | 0.01 | ns | ns |
| $\psi E_0$ | 0.542 ± 0.039 | 0.531 ± 0.054 | 0.516 ± 0.030 | 0.436 ± 0.046 | 0.488 ± 0.045 | 0.434 ± 0.048 | 0.03 | ns | ns |
| $\varphi E_0$ | 0.461 ± 0.037 | 0.453 ± 0.050 | 0.436 ± 0.029 | 0.361 ± 0.045 | 0.408 ± 0.041 | 0.361 ± 0.047 | 0.02 | ns | ns |
| $\delta R_0$ | 0.410 ± 0.069 | 0.353 ± 0.082 | 0.346 ± 0.058 | 0.435 ± 0.053 | 0.437 ± 0.039 | 0.414 ± 0.059 | 0.03 | ns | ns |
| $\varphi R_0$ | 0.191 ± 0.043 | 0.162 ± 0.049 | 0.152 ± 0.030 | 0.158 ± 0.033 | 0.178 ± 0.024 | 0.149 ± 0.024 | ns | ns | ns |
| RC/ABS | 0.479 ± 0.044 | 0.480 ± 0.057 | 0.471 ± 0.036 | 0.451 ± 0.046 | 0.525 ± 0.058 | 0.466 ± 0.072 | ns | ns | ns |
| $TR_0/DI_0$ | 5.657 ± 0.500 | 5.739 ± 0.517 | 5.480 ± 0.376 | 4.884 ± 0.721 | 5.130 ± 0.584 | 5.011 ± 0.858 | 0.32 | ns | ns |
| $ET_0/(TR_0 - ET_0)$ | 1.199 ± 0.182 | 1.158 ± 0.236 | 1.072 ± 0.124 | 0.783 ± 0.143 | 0.967 ± 0.178 | 0.778 ± 0.147 | 0.09 | 0.11 | ns |
| $PI_{ABS}$ | 3.316 ± 0.970 | 3.309 ± 1.166 | 2.807 ± 0.652 | 1.782 ± 0.626 | 2.670 ± 0.895 | 1.911 ± 0.737 | 0.45 | ns | ns |
| $\delta R_0/(1 - \delta R_0)$ | 0.717 ± 0.207 | 0.566 ± 0.179 | 0.538 ± 0.124 | 0.783 ± 0.165 | 0.783 ± 0.129 | 0.721 ± 0.164 | 0.09 | ns | ns |
| $PI_{TOTAL}$ | 2.499 ± 1.274 | 2.001 ± 1.114 | 1.537 ± 0.524 | 1.439 ± 0.708 | 2.082 ± 0.744 | 1.330 ± 0.551 | ns | ns | ns |

* ChlF parameters—chlorophyll *a* fluorescence parameters; all ChlF parameters abbreviations are described in Table 1. Tukey HSD test $_{GS}$—Tukey honestly significant difference test for growth stage, Tukey HSD test $_{FT}$—Tukey honestly significant difference test for fertilization treatment, Tukey HSD test $_{GS \times FT}$—Tukey honestly significant difference test for interaction between growth stage and fertilization treatment; ns—not significant.

## 3. Results and Discussion

Plants need the availability of essential micro- and macro-elements for normal growth and development and for maintaining physiological processes, including photosynthesis [51]. In this study, the in vivo chlorophyll *a* fluorescence transient was analyzed, by which the change in the light stage of photosynthesis in *Cannabis* plants with the presowing application of KCl and $K_2SO_4$ fertilizers was analyzed. The plants were grown in a field to gain insight into the real effect of KCl and $K_2SO_4$ fertilizers on the photosystem II (PSII) and photosystem I (PSI) functions based on the ChlF transients and parameters.

### *3.1. Chlorophyll a Fluorescence Transients*

The OJIP transients from the control industrial hemp leaves showed a typical polyphase rise with the basic steps of O-J-I-P. Both OJIP transients from the K fertilization *Cannabis* leaves showed deviations in steps I and J (Figure 4). Difference kinetics ΔV showed positive and negative trends depending on the K fertilization (Figure 4b–h). The L band and K band were positive in the flowering stage of the industrial hemp development. With the aging of the industrial hemp plants (ripening stage), the L and K bands became negative, with a greater pronounced influence when KCl ($K_1$) was applied. In the flowering stage of the industrial hemp, K fertilization reduces the energy connection of the PSII units (positive L band) [52].

On the other hand, at the ripening stage, the negativity of the L band indicates the opposite, which is why it can be said that the excitation energy was efficiently utilized, since the PSII units are more connected and better stability is created [50], which in this case was more pronounced when using KCl ($K_1$). Furthermore, K in flowering affected the deactivation of the oxygen-evolving complex and the increase in the size of the functional PSII antenna, as indicated by the positivity of the K band.

In this study, at the flowering stage, K affected the deactivation of the oxygen-evolving complex and the increase in the size of the functional PSII antenna, indicated by the positivity of the K band. However, the effect of K at the ripening stage with the occurrence of a negative K band is due to the faster transport of electrons on the donor side and/or the slower withdrawal of electrons from the acceptor side [53]. Also, in the I, H, and G bands, the curves behave the same way according to the stages of the industrial hemp development. The above bands provide insight into PSI's functioning and the reoxidation of the PQ pool from the PSI carrier. In the flowering stage, the I band is positive except for $K_2SO_4$ at the ripening stage. Changes from positive and negative bands and vice versa occurred at the ripening stage of the industrial hemp with a different reaction to KCl ($K_1$), and $K_2SO_4$ ($K_2$) fertilization. The influence of K fertilization can be seen most strongly in the H band. $K_2SO_4$ had a greater influence on the H band both at the flowering and ripening stages of the industrial hemp (greater deviations were created compared to the KCl treatment). The positivity of the H band indicates a decrease in PQ pool capacity and a higher reduction rate. On the other hand, the negative band represents an increase in the PQ pool [54].

In the case of the G band, in addition to the differences between the growth stages, a difference was found based on the applied fertilizer formulation, which caused a decrease in the PSI acceptor pool with reduced electron transport [53,55].

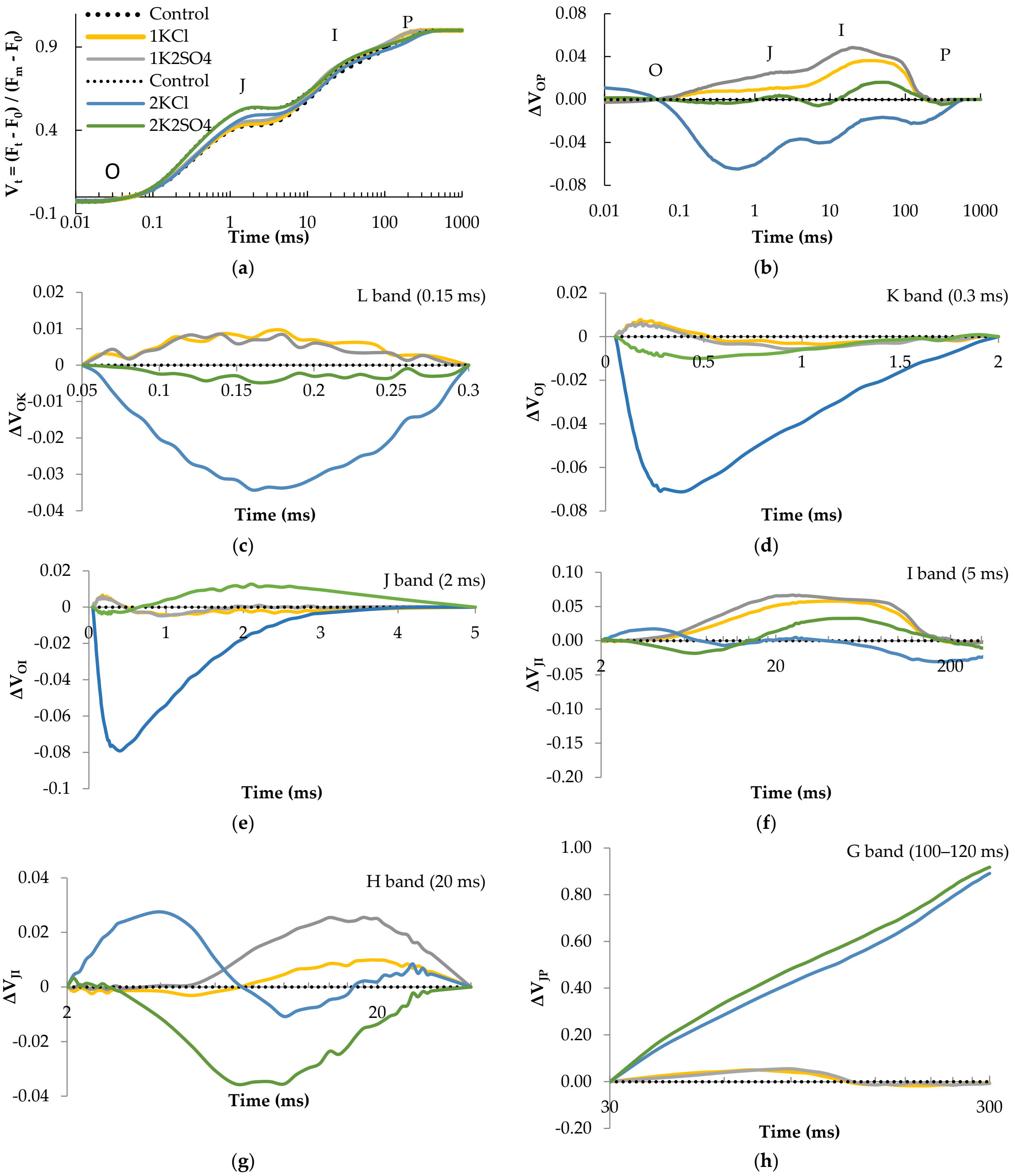



**Figure 4.** Expression of *Cannabis* plant response to KCl and $K_2SO_4$ soil fertilization in two growing stages (1—flowering; 2—ripening stage) are presented as kinetics of relative variable fluorescence $V_t$ and as difference kinetics $\Delta V_{OP}$ (**a**,**b**). Difference kinetics $\Delta V_t$, for individual bands, L (**c**), K (**d**), J (**e**), I (**f**), H (**g**), and G (**h**) are plotted at different time ranges. Each curve represents the average of ten measurements ($n$ = 10) per treatment and growth stage. The control values (treatment without fertilization) per growth stage were used as referent values. The O, J, I, and P steps are indicated in $V_t$ and $\Delta V_{OP}$ curves.

### *3.2. Chlorophyll a Fluorescence Parameters*

Two-factorial ANOVA was used to determine the significance of the sources of variability: the growth stages (flowering and ripening), the fertilization treatments ($K_0$, $K_1$, and $K_2$), and the interactions between the growth stages and fertilization treatments. The response of the chlorophyll *a* fluorescence parameters in the industrial hemp leaves based on the different K fertilizer doses at the two growth stages is presented in Table 2.

Significant minimum initial fluorescence ($F_0$) differences were confirmed only for the KCl ($K_1$) treatment. The control ($K_0$) and $K_2SO_4$ ($K_2$) groups were not statistically different, but KCl showed a trend of being 12.33% lower than the $K_0$ treatment. The interaction between the growth stages and fertilization treatment was found to be significant for the ripening stage when KCl fertilizer was applied and, compared to the $K_0$ and $K_2SO_4$ ($K_2$), the KCl ($K_1$) treatment affected $F_0$ by lowering the value, especially at the ripening stage. Then, it was 23.8% lower compared to the controls in the ripening stage. Generally, fertilization with K lowered the $F_0$ values in both growth stages compared to the $K_0$ treatment. This is also in accordance with the research of Kusaka et al. [56], which found that a lack of K causes an increase in the $F_0$ value in *Raphanus sativus* var. *sativus*.

Maximum fluorescence ($F_m$) varied significantly in response to the growth stage and fertilization treatment. The ripening stage and KCl ($K_1$) treatment were statistically different. The highest $F_m$ value was determined in the flowering growth stage when applying $K_2SO_4$ ($K_2$), which was 4036 (relative units). The interaction revealed a significant difference in KCl ($K_1$) at the ripening stage, with the lowest $F_m$ being 26.7% lower than in the $K_0$ treatment. In the flowering of the industrial hemp, he treatments with K increased the $F_m$, but the $F_m$ value decreased at the ripening stage, which, according to Kalaji et al. [57], indicates the accumulation of inactive RC on PSII. Kusaka et al. [56] achieved lower $F_m$ values in younger and older radish leaves due to K deficiency. The behavior of the $F_0$ and $F_m$ values in this study confirmed that the industrial hemp plants, in both fertilization variants, KCl and $K_2SO_4$, were sufficiently supplied with K. Hence, their values decreased under the influence of K.

The logical sequence of the behavior of $F_0$ and $F_m$ in the fertilization treatments and growth stages also confirmed the significance of $ET_0/(TR_0 - ET_0)$ for the growth stage and treatment. These two parameters exactly determine $ET_0/(TR_0 - ET_0)$, i.e., electron transport from $Q_A$ to the intersystem electron acceptors [49]. The difference between the KCl and $K_2SO_4$ treatments was 12.98%, with the highest values being seen in the KCl treatment. On the other hand, at the ripening stage, $ET_0/(TR_0 - ET_0)$ decreased by 26.25%.

Electron transport flux to the PSI acceptors ($RE_0/RC$) was confirmed to have a statistically significant difference in the fertilization treatment as a source of variability. The value of $RE_0/RC$ decreased with the application of KCl by 9.4% and 13.7% with the application of $K_2SO_4$. Also, reduced values of $RE_0/RC$ were found in K deficiencies during the cultivation of radish [56]. The decrease in $RE_0/RC$ that occurred due to the presence of K in the soil, which the plant adopted, describes the impaired movement of electron transport from $Q_A^-$ to the end electron acceptors on the PSI acceptor side.

The absorption flux per active RC (ABS/RC), trapping flux per active RC ($TR_0/RC$), quantum yield of electron transport from $Q_A^-$ to the PSI end electron acceptors ($\varphi R_0$), density of RC on chlorophyll *a* basis (RC/ABS), and the performance index for energy conservation from the absorption all the way to the reduction in PSI end acceptors ($PI_{TOTAL}$) were not significant, regardless of the sources of variability. The mentioned parameters showed stability regardless of the testing conditions and performed their activities normally, i.e., were undisturbed. Although $PI_{TOTAL}$ is known as the most sensitive ChlF parameter since it includes the most important functional steps of primary photochemistry and, hence, the vitality of photosynthetic units [50], this study did not show that PItotal was not affected by K fertilization or growth stage of industrial hemp. Researching nutrient deficiency in maize revealed that K deficiency did not significantly affect any of the tested photosynthetic ChlF parameters [58].

Furthermore, the treatments did not show significance, unlike the growth stage, which was significant for a maximum quantum yield of primary efficiency ($\varphi P_0$), flux ratio trapping per dissipation ($TR_0/DI_0$), the performance index for energy conservation of the reduction in intersystem electron acceptors ($PI_{ABS}$), electron transport flux per active RC ($ET_0/RC$), the probability that a trapped exciton moves an electron into the electron transport chain beyond $Q_A$ ($\psi E_0$), quantum yield for electron transport ($\varphi E_0$), dissipated energy flux per active RC ($DI_0/RC$), the probability that an electron is transported from the reduced PQ to the electron acceptor side of the PSI ($\delta R_0$), and electron transport from $PQH_2$ to the final PSI acceptors ($\delta R_0/(1 - \delta R_0)$). Kalaji et al. [58] also found no difference in ChlF parameters in K application to greenhouse-grown maize in nutrient solution. Also, a study of responses to nitrogen fertilization in *Cannabis sativa* suggests that although N affected the leaf N and chlorophyll content, the fluorescence parameters evaluated under field conditions remained unchanged [59].

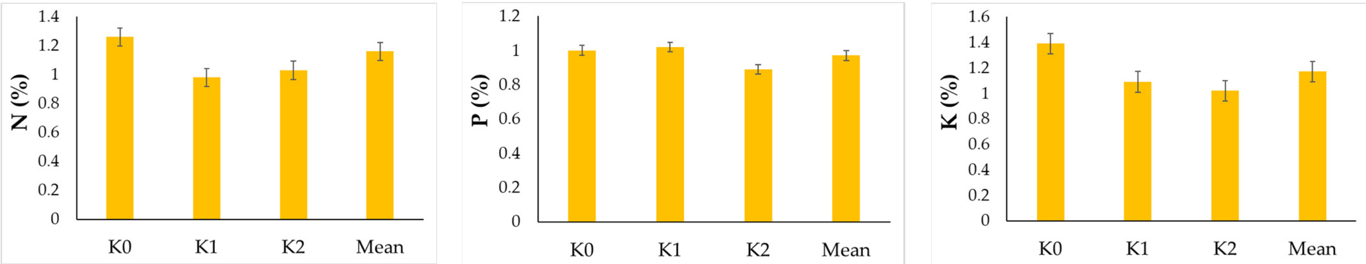
The results of this study showed that the *Cannabis* plants had different values of $\varphi P_0$, $TR_0/DI_0$, and $PI_{ABS}$ according to the treatments, which did not show significant differences compared to the controls ($K_0$). However, the $ET_0/RC$, $\psi E_0$, $\varphi E_0$, $\varphi P_0$, $TR_0/DI_0$, and $PI_{ABS}$ parameters had higher values in the flowering stage, which was significant. $ET_0/RC$ was lower by 16.84%, $\psi E_0$ by 14.43%, $\varphi E_0$ by 16.22%, $\varphi P_0$ by 2.01%, $TR_0/DI_0$ by 10.97%, and $PI_{ABS}$ by 32.54% compared to the flowering stage. This means that the activities of these parameters decrease with aging in industrial hemp plants. Also, $DI_0/RC$, $\delta R_0$, and $\delta R_0/(1 - \delta R_0)$ showed statistical differences per growth stage, but their behavior was contrary to the abovementioned parameters. The ripening stage of the plant growth caused higher $DI_0/RC$, $\delta R_0$, and $\delta R_0/(1 - \delta R_0)$ values by 1.42%, 15.68%, and 25.54%, respectively, i.e., their activities increase as the industrial hemp plants age.

$PI_{ABS}$ shows the vitality of the photosynthetic units, which is why this is known as a very sensitive parameter [50]. Also, a very representative ChlF parameter in research is $\varphi P_0$, which proved less sensitive than $PI_{ABS}$. The reason for the same trend in the behavior of the mentioned parameters is that the behavior of $\varphi P_0$ accompanies the changes in $TR_0/DI_0$ and $PI_{ABS}$ because the values of $\varphi P_0$ are used for the $TR_0/DI_0$ and $PI_{ABS}$ calculation. Likewise, observing the parameters of electron transport ($ET_0/RC$, $ET_0/TR_0$, and $ET_0/ABS$), the same conclusion was established because for the calculation of $ET_0/ABS$, the $\varphi P_0$ and $ET_0/TR_0$ data are used, and for $ET_0/RC$ the $ET_0/TR_0$ data are used. This is the same with the calculation $\delta R_0/(1 - \delta R_0)$, for which the values of $\delta R_0$ are used. This is the cause of the same behavior of the parameters according to the stages of growth and fertilization with K. Seliem et al. [60] found greater effectiveness in stimulating the vegetative growth of saffron when using different doses of K-silicate compared to K-sulfate. From the other point of view, precisely with this connection between the parameters, their changes according to the growth stages of the industrial hemp plants are visible. Earlier, a change in the tendency of the behavior of the parameters by growth stage was determined because the senescence of plants leads to changes in the behavior of the ChlF parameters, which also occurred in this research. The decrease in the value of the photosynthetic index and accompanying parameters with the aging of the industrial hemp plants, more precisely in the maturity stage, resulted in a loss of photosynthetic efficiency. The redox reaction after $Q_A$ was inhibited, leading to additional electron transfer impairment between $Q_A$ and $Q_B$. Likewise, the industrial hemp aging shows an increase in the parameters describing the flow of electrons in PSI, $\delta R_0$, and $\delta R_0/(1 - \delta R_0)$. $\delta R_0$ depends on the electrons transferred to PSI from $PQH_2$ and the influx of electrons from the upper electron carrier. The aging-induced increase in $\delta R_0$ results from fewer donated electrons for $PQH_2$ reduction. During the senescence of *Alhagi sparsifolia* (Fabaceae) and wheat, photosynthesis efficiency and electron transfer changes were also detected [61,62].

Other photosynthetic parameters have been observed for industrial hemp. Struik et al. [35] found that industrial hemp radiation uses efficiency (PAR) changed throughout the season and reported that PAR decreased in earlier cultivars after flowering.

### *3.3. Chemical Composition of the Stem*

The average content of macronutrients in the stem at the maturity stage was 1.16% N, 1.07% P, and 1.17% K (Figure 5). The K content was lower by 21.58% with KCl ($K_1$) and 26.62% lower with $K_2SO_4$ ($K_2$) compared to the control treatment ($K_0$). According to Iványi and Izsáki [63], in Hungary, which is close to this experimental station, the optimal time for collecting samples to determine micronutrient status in industrial hemp leaves is late May and early June, when satiation can be found if the leaves contain 5–6% N, 0.5–0.6% P, and 2.7–3.0% K.




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

**Figure 5.** The macronutrient content (N, P, and K) in different industrial hemp stem samples ($K_0$—control, $K_1$—KCl, $K_2$—$K_2SO_4$) (**a**) N (%), (**b**) P(%) and (**c**) K (%). Vertical error bars indicate a standard error of 5%.

In the present study, it was found that for both N and K, the content was highest in the control treatment (Figure 5a,c). Light et al. [64] reported that, even though the reason is not clear, there is a certain antagonism between N and Cl taken up by the crop, since it was found that N deficiency occurs when soil Cl is high. This may be the reason for the lowest N uptake by the industrial hemp plants in this study on the KCl treatment, even though the differences were not significant among the K sources (Figure 5a). In the present study, the highest concentrations of the other macronutrients, P and K, were determined for the industrial hemp in the $K_0$ treatment. Zehler et al. [37] stated that the uptake of the $K^+$ ions is 1.28 mEq with KCl, and is lower, at 0.74 mEq, with $K_2SO_4$. This may be the reason for the lower K accumulation in the present study for the industrial hemp stem at harvest, due to the lower uptake of the K fertilizer source (Figure 5c).

According to Wilmer et al. [65], KCl in water dissociates into potassium ($K^+$) and chloride ($Cl^-$) ions, which contributes to a higher osmotic concentration compared to $K_2SO_4$, which dissociates into $K^+$ and sulfate ions ($SO_4{}^{2-}$); thus, it may have an effect on water uptake and growth rates. Zehler et al. [37] stated in the case of nutrients such as K, the influence on the plant may depend on how it is chemically combined within the fertilizer with additional substances such as S and Cl. Naila Farooq et al. [66] argued that Cl content from KCl fertilizers may be a problem in arid and semiarid areas, due to salinity, so the authors recommend blending the KCl with composts, which significantly mitigates the salinity risks associated with the $Cl^-$ ions and boosts nutrient availability, maize plant growth, and chlorophyll content. In sorghum plants, Amasiab et al. [67] found that with $K_2SO_4$ application (0, 10, 20, 30, 40, and 50 kg/ha), the content of the N in forage significantly ($p < 0.01$) increased from 1.4% (control) to 2.14% (50 kg/ha), which suggests that enhanced N content improves protein content, which is critical for forage quality. In the present study, the N content was slightly higher with the $K_2SO_4$ ($K_2$) application as compared to the KCl ($K_1$) treatment, but still, the content was decreased in comparison with the control ($K_0$) treatment. Bakhsh et al. [68] found some differences in the source of K fertilizer for cereals. Thus, the authors stated that 37 kg K/ha of KCl was most effective in rice, wheat, and fallow–wheat rotations, whereas 37 kg K/ha of $K_2SO_4$ performed better in the maize–wheat rotation. Moreover, the authors stated that overall $K_2SO_4$ out-yielded KCl, likely due to the additional benefits of the sulfate ($SO_4{}^{2-}$) ion in improving nutrient availability and mitigating calcareous soil constraints. In calcareous and alkaline soils, Liu et al. [69] found that the potato tuber yield increased by 7.4% (200 kg/ha $K_2SO_4$) and even more, by 21.5% (300 kg/ha $K_2SO_4$), in comparison with the control treatment. Thus, the authors stated that K accumulation in critical growth stages such as tuber formation and starch accumulation was strongly correlated with increased potato yields, but also the application of $K_2SO_4$ significantly decreased soil pH, which enhanced phosphorus availability in calcareous soils.

### *3.4. Morphometric Parameters and Yield*

In order to determine whether the formulation of K fertilizer affects the morphological properties of the stem and the chemical composition and fibers in the stem of industrial hemp, K fertilizer in two forms was applied as a presowing treatment. Generally, the effect of KCl and $K_2SO_4$ was not highly different for the morphometric parameters in this study. The different K fertilization sources did not significantly influence the number of plants per unit area. According to the results of this research, the average number of plants per unit area was 92,000 plants ha$^{-1}$ (Table 3).

**Table 3.** The number of plants per unit area at harvest.

| Treatment | No. Plants ha$^{-1}$ | No. Male Plants ha$^{-1}$ | No. Female Plants$^{-1}$ |
|---|---|---|---|
| $K_0$ | 82.000 | 25.333 | 56.667 |
| $K_1$ | 96.333 | 30.667 | 65.667 |
| $K_2$ | 97.667 | 43.333 | 54.333 |
| Mean | 92.000 | 33.111 | 58.889 |
| LSD $_{(0.05)}$ | ns | ns | ns |

Note: ns—non-significant.

The average share of male plants was 36% of the plants, while the number of female plants was 64%. Tang et al. [70] reported that for industrial hemp, the stem was higher at a lower density (45 plants ha m$^{-2}$) in comparison with the highest sowing density (67.5 plants m$^{-2}$). For industrial hemp for fiber production, Augustinović et al. [33] found that increasing plant density (from 100 to 300 seeds m$^{-2}$) resulted in a higher share of non-sprouted seeds, which confirms that that fewer hemp plants survive denser sowing, i.e., a denser plant population after sprouting. According to Ranogajec et al. [71], in the period from 2014 to 2023, the average industrial hemp seed yield in Croatia varied from 0.4 t ha$^{-1}$ (2014) to 1.5 t ha$^{-1}$ (2023). Thus, based on the results of the present study, the seed yield was a little higher than the average yield in Croatia for 2023. The K treatment did not significantly influence the stem morphological parameters or stem and seed yield (Table 4). Even though the $K_1$ treatment did not significantly influence the morphometric parameters, the stem height, stem diameter, and stem and seed yield were on average the lowest as compared to the other K treatments (Table 4).

**Table 4.** Industrial hemp stems' morphometric and agronomic parameters.

| Treatment | Stem Height (cm) | Stem Diameter (cm) | Stem Yield (t $ha^{-1}$) | Dry Stem Yield (t $ha^{-1}$) * | Seed Yield (t $ha^{-1}$) |
|---|---|---|---|---|---|
| $K_0$ | 79.7 | 0.45 | 16.0 | 11.9 | 1.96 |
| $K_1$ | 52.0 | 0.38 | 15.7 | 12.5 | 1.76 |
| $K_2$ | 79.7 | 0.39 | 17.0 | 12.2 | 1.82 |
| Mean | 67.5 | 0.41 | 16.2 | 12.2 | 1.85 |
| $LSD_{(0.05)}$ | ns | ns | ns | ns | ns |

Note: * air-dried mass per hectare; ns—non-significant

According to Vukadinović and Vukadinović [72], with a good supply of K for plants, the net assimilation is increased with a faster synthesis of reserve substances such as starch, sucrose, lipids, and proteins, but a K increase also strengthens of the plant and its turgor generation and helps it to resist drought and diseases, which is important for a high and stable yield of field crops. One of the most important roles of K is reducing stalk lodging for all field crops. Inadequate K fertilization leads to different stresses, such as water deficit. For industrial hemp, there is no newer literature about the influence of K formulation on stem yield and seed yield. According to Pasković [37], there was a recommendation for industrial hemp cultivation for fiber that it is better to avoid K from KCl fertilizer due to the harmful influence of Cl in K fertilizer, which leads to an increase in the volume of fiber groups and individual fiber cells. The volume expands, and the cell wall narrows so that the entire set of fibers becomes loose due to the deformed cells with a round or ovoid cross-section. Aubin et al. [34] found that K fertilization of industrial hemp has very limited or no influence on biomass and seed yield. Tsaliki et al. [73] stated that the productivity of industrial hemp is strongly affected by genotype and environmental conditions in Mediterranean conditions. Moreover, the authors reported that the industrial hemp stem of six genotypes (Santhica 27, Futura 75, Felina 32, Tygra, Bialobrzeskie, and Fedora 17) in a 3-year study was on average 5.7 mm and stem yield of 14.4 t $ha^{-1}$. Stack et al. [74] highlighted the importance of morphological and chemical compound traits among cultivars to gather data for plant breeders, especially on female inflorescences of *Cannabis sativa*. In Hungary, Iványi and Izsáki [64] reported that weather conditions have a great influence on industrial hemp stem yield, which was 12–17 t $ha^{-1}$ in a year with adequate precipitation, while in a year with lower precipitation, the yield was 6–8 t $ha^{-1}$. Kołodziej et al. [18] showed that different sowing rates significantly influence stem yield. Hence, the authors stated that between different sowing rates (from 5 to 60 kg $ha^{-1}$), the authors recommended 30 kg $ha^{-1}$ as an optimal sowing rate when hemp yielded 14.65 t $ha^{-1}$. Campiglia et al. [75], in a study of several varieties (Epsilon68, Fedora17, Felina32, Ferimon, Futura75, Santhica27, and Uso31) in Mediterranean conditions, found the dry stem yield was on average from 3.4 to 8.0 t $ha^{-1}$ of dry matter and further found that stem diameter was inversely correlated with plant density (6.7, 5.8 and 5.2 mm at 40, 80, and 120 plants $m^{-2}$, respectively). For the industrial hemp Finola variety, Varga et al. [76] found that stem diameter was on average 3.4 mm and the plant height was 71.2 cm, and that the seed mass per plant was significantly correlated ($p < 0.05$) with plant height with the application of $K_2SO_4$ fertilizer.

Saloner and Bernstein [77] examined secondary metabolites in different K supplies (15, 60, 100, 175, and 240 mg $L^{-1}$ K) of medicinal hemp and found that cannabinoid and terpenoid content decreased with the elevation of K supply. According to a study by Finnan and Burke [78], K supply did not significantly influence industrial hemp fiber yield. Ahmadi et al. [36] confirmed similar findings for K. According to the authors, K does not significantly influence plant biomass and seed yield, but this does not diminish its role as an essential element for plant growth. Light et al. [64] stated that $Cl^-$ and $SO_4^{2-}$ ions can leach more rapidly in the soil system, and the adsorption of the $SO_4^{2-}$ ions is more rapid in the plant tissue, occurring at a greater rate than for $Cl^-$ ions. The formulation of K fertilizer proved to be important for several field crops such as potatoes [79], cotton [80], tobacco [81], tomato [82], and pepper [83] in terms of the way that chloride-free K fertilizers should be applied. $K_2SO_4$ instead of KCl for potatoes is preferred because $Cl^-$ in the fertilizer can delay tuber development and decrease tuber yield [84]. Light et al. [64] mitigated the negative impact of KCl and found that KCl use did not influence potato quality. In a sugarcane pot experiment, Watanabe et al. [85] reported that sucrose concentration was reduced with KCl fertilizer but increased by $K_2SO_4$ fertilization. Hüvely and Vojnich [86] stated that chloride ions are generally harmful to vegetables such as pepper and that K sulfate is preferred ($K_2SO_4$). On the other hand, $Cl^-$ is an essential element and, in some research, is found to influence plant development positively, but in higher doses, it can have a negative effect on plant growth, especially in early growth stages [87]. Fixen [88] reported that in wheat and barley, $Cl^-$ is attributed to the suppression of the root and gives plants tolerance to disease. The amount of N has a greater influence on stem and seed yield formation than K. Wylie et al. [89] reported that up to 200 kg N $ha^{-1}$ could increase plant height, stem diameter, biomass, and seed yields and that, on the contrary, 60 kg N $ha^{-1}$ is sufficient for dual-purpose cultivars. Tang et al. [61] reported that fertilization rates over 300 kg $ha^{-1}$ were not justified and that they even resulted in a higher level of stem bark content, concluding that the nutrient ratio should be a N:P:K ratio of 3:1:2, rather than 4:1:2.

### *3.5. Tensile Strength and Stiffness of Industrial Hemp Stem*

After the two different K fertilization treatments (KCl and $K_2SO_4$), samples of the dry industrial hemp stems were subjected to tensile tests. The results were compared with samples that had not been fertilized ($K_0$). Each group consists of three test samples (Figure 6a). The relationship between stresses and strains are shown in Figure 6. Figure 6b shows samples of the industrial hemp after tensile failure.

In order to understand and observe the mechanical behavior of industrial hemp stem, tensile strength and the modulus of elasticity were determined. For this purpose, the middle part of the stem was taken for measuring. The tensile strength of the individual samples ranged from 38.23 to 63.59 MPa (Table 5). This is a result of the naturally heterogeneous and highly variable nature of industrial hemp stems. Unfertilized hemp has an average tensile strength of 51.78 MPa, KCI-fertilized hemp has a tensile strength of 49.25 MPa, and $K_2SO_4$-fertilized hemp has a tensile strength of 53.32 MPa.

The modulus of elasticity was determined based on linear regression lines placed on the elastic part of the stress–strain curve (Figure 7). The average modulus of elasticity equals 4.99 GPa for IH-K0, 5.06 GPa for IH-KCl, and 5.07 GPa for IH-$K_2SO_4$. The highest modulus of elasticity was obtained for sample IH-KCl-1 and was 6.51 GPa, while the lowest value of 3.37 GPa was obtained for sample IH-KCl-2.

Iványi and Izsáki [64] reported that N and K fertilization for industrial hemp leads to longer and thicker stems and higher fiber yield. Shah et al. [41] argue that the mechanical properties of plants are not only important for phenotyping but also for harvest and processing due to stem interaction with machines. Galedar et al. [43] highlighted that for alfalfa (*Medicago sativa* L.) tensile strength increased exponentially with a decrease in the moisture content and towards the lower regions, and that for the middle part of the stem, the tensile strength varied from 16.31 and 32.74 MPa.

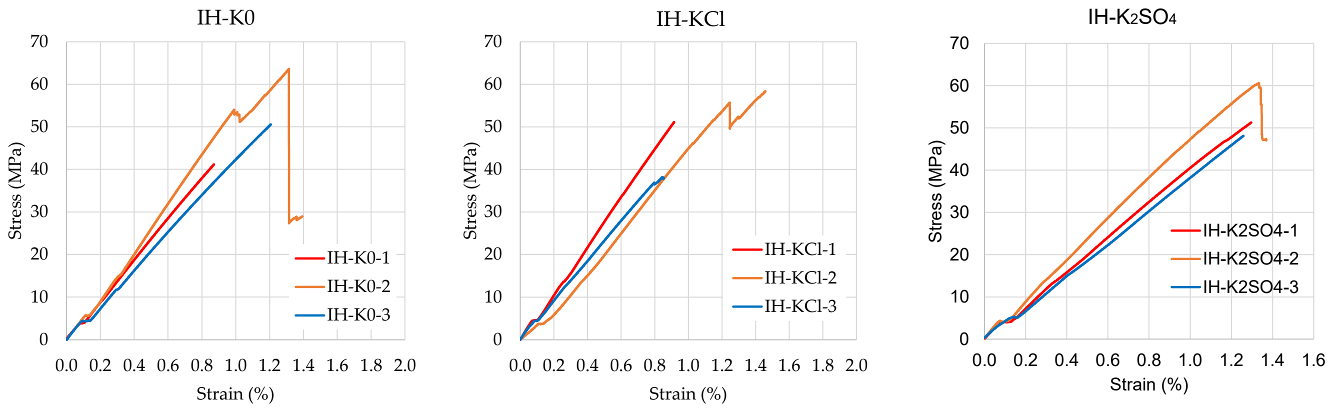

(**a**)


(**b**)

**Figure 6.** Industrial hemp samples (**a**) before performing the tensile test and (**b**) after the tensile test.

**Table 5.** Tensile properties of industrial hemp stem.

| Sample | Max $F_c$ (N) | Average Cross-Section (mm$^2$) | Tensile Strength (MPa) | Average Tensile Strength (MPa) | Young's Modulus (GPa) | Average Young's Modulus (GPa) |
|---|---|---|---|---|---|---|
| IH-$K_0$ (control treatment) | | | | | | |
| IH-K0-1 | 1055 | 25.61 | 41.18 | 51.78 | 4.77 | 4.99 |
| IH-K0-2 | 1095 | 17.72 | 63.59 | | 5.19 | |
| IH-K0-3 | 1052 | 20.80 | 50.57 | | 5.02 | |
| IH-KCl treatment | | | | | | |
| IH-KCl-1 | 921 | 18.01 | 51.14 | 49.25 | 6.51 | 5.06 |
| IH-KCl-2 | 1337 | 22.91 | 58.37 | | 3.37 | |
| IH-KCl-3 | 945 | 24.76 | 38.23 | | 5.29 | |
| IH-$K_2SO_4$ treatment | | | | | | |
| IH-$K_2SO_4$-1 | 1066 | 20.79 | 51.27 | 53.32 | 5.15 | 5.07 |
| IH-$K_2SO_4$-2 | 1272 | 21.00 | 60.57 | | 6.00 | |
| IH-$K_2SO_4$-3 | 836 | 17.38 | 48.12 | | 4.05 | |




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

**Figure 7.** Stress–strain diagrams for industrial hemp stem: (**a**) IH-K0, (**b**) IH-KCl, and (**c**) IH-$K_2SO_4$.

### *3.6. Correlation Analysis of Industrial Hemp Stem*

Correlation analysis showed a significant relationship between several parameters (Table 6). The highest very significant correlation coefficients were determined for industrial hemp macronutrient status (N, P, and K).

**Table 6.** Pearson's correlation coefficients.

| | No. of Plants Per Unit Area | Stem Height | Stem Diameter | Seed Yield | Stem Yield | N | P | K | Max Fc (N) | Average Cross-Section | Tensile Strength (MPa) | Young's Modulus (GPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. of plants per unit area | 1 | | | | | | | | | | | |
| Stem height | −0.395 ns | 1 | | | | | | | | | | |
| Stem diameter | −0.506 ns | 0.674 * | 1 | | | | | | | | | |
| Seed yield | 0.003 ns | 0.494 ns | 0.242 ns | 1 | | | | | | | | |
| Stem yield | 0.688 * | −0.307 ns | −0.556 ns | −0.302 ns | 1 | | | | | | | |
| N | −0.029 ns | 0.199 ns | 0.504 ns | 0.332 ns | −0.208 ns | 1 | | | | | | |
| P | −0.204 ns | 0.245 ns | 0.721 * | 0.354 ns | −0.372 ns | 0.808 ** | 1 | | | | | |
| K | −0.007 ns | 0.114 ns | 0.519 ns | 0.430 ns | −0.163 ns | 0.841 ** | 0.903 ** | 1 | | | | |
| Max Fc (N) | 0.223 ns | −0.536 ns | −0.525 ns | −0.548 ns | 0.486 ns | 0.041 ns | −0.051 ns | 0.051 ns | 1 | | | |
| Average cross-section | 0.147 ns | −0.022 ns | 0.081 ns | 0.293 ns | −0.170 ns | 0.264 ns | 0.308 ns | 0.431 ns | 0.308 ns | 1 | | |
| Tensile strength (MPa) | 0.025 ns | −0.441 ns | −0.488 ns | −0.653 * | 0.565 ns | −0.117 ns | 0.613 * | 0.305 ns | 0.613 * | −0.545 ns | 1 | |
| Young's mod-ulus (GPa) | −0.158 ns | 0.127 ns | −0.097 ns | 0.413 ns | −0.306 ns | 0.170 ns | 0.218 ns | 0.173 ns | −0.218 ns | −0.214 ns | 0.021 ns | 1 |

Note: ns—non-significant; * significance 0.05; ** significance 0.01.

Macronutrients play indispensable roles in plant growth and development, acting as structural components, energy carriers, and catalysts for biochemical processes. Nadeem et al. [90] stated that K is highly mobile within the plant and essential for younger plant parts, regulation of water uptake and transport, enzyme activation, and photosynthesis.

Nitrogen in the plants positively influences P uptake, but P deficiency negatively affects $NO_3^-$ uptake from the soil [91–93]. Schleuss et al. [94] and Xie et al. [95] stated that plants often use N instead of P and vice versa, which can explain the synergistic plant growth responses to NP fertilization. Plant-available K in the soil (exchangeable K) has a considerable influence on N uptake [96]. The $NH_4^+$ and $K^+$ share similar valence and size properties in long-distance transport within the plant [97], which can explain the positive correlation of those elements in the industrial hemp stem determined in this study. For industrial hemp morphometric parameters and seed and stem yield, the significant ($p < 0.05$) correlation coefficients were determined for the number of plants per unit area and seed yield (r = 0.688), stem height, and diameter (r = 0.674). The stem diameter was positive, and there was a significant correlation with the amount of P in the stem dry matter (r = 0.721). Seed yield was in negative and significant ($p < 0.05$) correlation with tensile strength (r = −0.653).

## 4. Conclusions and Future Perspectives

Fertilization is a necessary agricultural practice that makes cultivating the desired crop more successful. This study aimed to analyze the influence of different K fertilizer formulations on the photosynthetic activity of industrial hemp leaves and stem morphology and biomechanics. Even though the forms of K fertilization that were used had no significant effect on the differences between the morphological parameters or stem and seed yield, further trials should be conducted on the application of macronutrients to Finola varieties. Although the tensile strength and module elasticity were not homogeneous, these results are valuable for the harvesting and further processing of the stems. These findings are very valuable considering the differences in cost between KCl (which is a little cheaper) and potassium fertilizers containing sulfate, like $K_2SO_4$, which can certainly play a major role in agricultural decision-making. By using KCl as a fertilizer, farmers can reduce the costs of cultivation significantly, especially for crops that are not sensitive to chloride. In the present study, the industrial hemp variety Finola did not show any extreme influence regard the KCl application; thus, it can be recommended for future use in industrial hemp production.

In general, the applied KCl doses showed lower values than the control and $K_2SO_4$ for half of the chlorophyll *a* fluorescence parameters in the industrial hemp leaves. On the other hand, the values of the ChlF parameters measured at the maturity stage were mostly lower than those measured at the flowering stage. Although there were some changes in the efficiency of the photosystems I and II, our next step is to investigate the effect of higher doses of K fertilizers to gain insight into the photosynthetic activity at a higher level of availability of K from the soil to the cannabis plants.

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