

Article

Agronomic Practices to Maximize Seed and Straw Yield of Monoecious Hemp Cultivar ‘Henola’

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Abstract

Hemp (*Cannabis sativa* L.), as a valuable source of biomass, has been utilized for textile purposes, the production of environmentally friendly polymeric materials, modern composites, and paper. Moreover, hemp can be used for biofuel production. Therefore, optimal conditions for the cultivation of hemp varieties are essential. The aim of this study was to optimize agronomic practices—sowing date, row spacing, and mineral fertilization—to maximize straw and seed yield of the monoecious hemp cultivar ‘Henola’ under temperate climate conditions. Field experiments were conducted over three growing seasons using a randomized block design, testing five fertilization treatments, three sowing dates, and three row spacings. Statistical analysis revealed that high nitrogen doses (PK + 120 N) significantly increased both straw and seed yields. The optimal sowing period was from late April to early May. Narrower row spacings (0.2 m and 0.35 m) favored higher seed yields, while row spacing had no significant effect on straw biomass. These findings support the development of evidence-based recommendations for maximizing hemp yield depending on end-use objectives.

Keywords: *Cannabis sativa* L.; fertilization; row spacing; sowing date; biomass; agronomy



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1. Introduction

Plant biomass is widely used for the production of fuels, chemicals, food, and fodder. Global demand for biomass materials is constantly growing; therefore, new sources are being sought [1]. The vast amount of waste biomass generated by the agricultural sector is considered the most abundant and economically viable renewable resource [2]. European bioeconomy strategies are increasingly embracing the concept of a circular bioeconomy to ensure the resource-efficient use of biomass. It is expected to play a key role in achieving global climate goals [3].

The diversity of *Cannabis sativa* L. in terms of varieties and their requirements means that it can be successfully cultivated in many different regions around the world [4]. Hemp and its cultivation have been gaining popularity in recent years. Currently, the largest hemp producers are Canada (18,550 ha) [5], the USA (28,314 ha) [6], and China (18,749 ha) [7]. In Europe, according to the latest Eurostat data from 2022 [8], the leading producers were France, Germany, and the Netherlands, with cultivation areas of 19,560 ha, 5600 ha, and 1700 ha, respectively. The acreage of hemp crops in these countries is also significantly increasing [9]. In most countries, not only domestic varieties are cultivated. For example,

Polish hemp varieties are popular both in Europe and North America, especially due to their stable monoeciousness and high yield potential [10]. The growing interest in hemp cultivation is undoubtedly related to the increasing demand for natural products derived from local and renewable sources. Hemp fits perfectly into this trend, as every part of the plant can be effectively utilized. Hemp raw materials are used in almost every sector of the economy. Therefore, a further increase in the acreage of hemp cultivation is projected [11,12].

Hemp is an annual plant, meaning it renews its biomass every year [13]. According to various sources, depending on climatic and soil conditions, variety, and plantation type, the average hemp straw yield ranges from approximately 10 to even 20 Mg·ha⁻¹ [14–16]. Given the ever-increasing demand for energy and the shift from non-renewable to renewable sources, hemp is undoubtedly a valuable source of biomass. The potential applications of hemp biomass are illustrated in Figure 1.

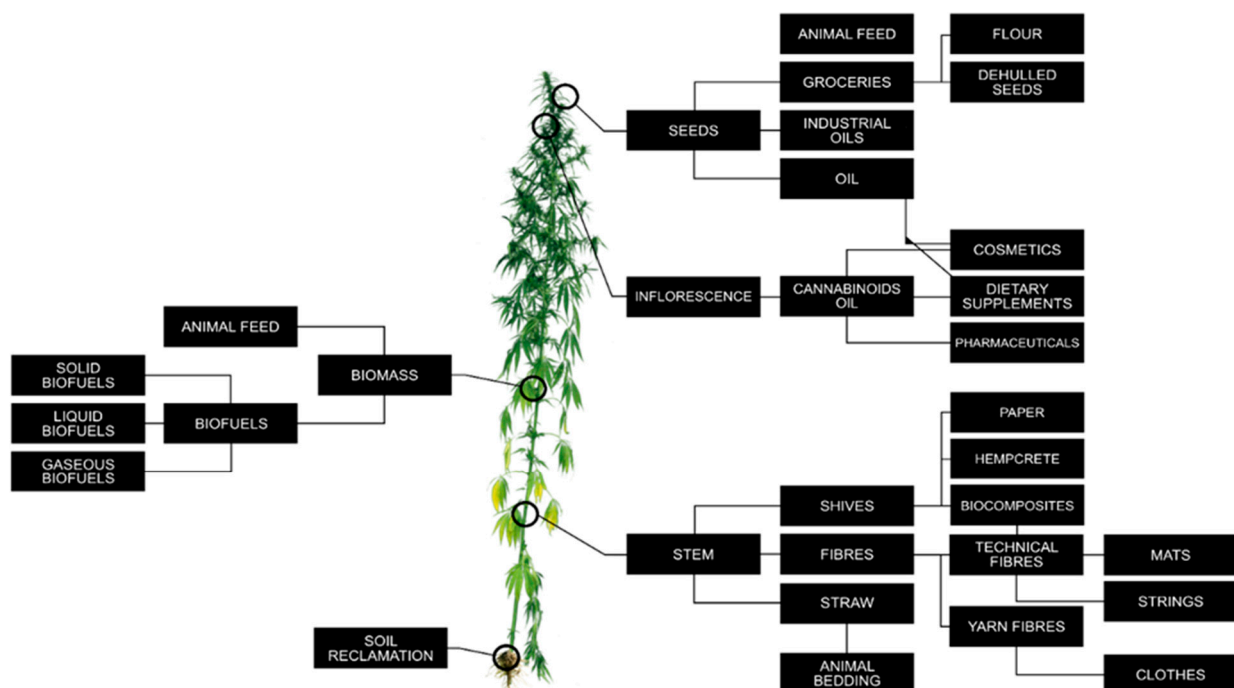


Figure 1. Possibilities for using hemp biomass [17].

Hemp is a rich source of natural substances that can be used in many branches of industry [18]. It has traditionally been used for textile purposes, and this trend has been regaining importance in recent years [19]. Due to the high availability, low cost, and renewable nature of natural fibers, hemp biomass has become one of the most popular components for the production of environmentally friendly polymeric materials and modern composites [20–22], for example, those used to absorb sound or reduce fire risk [23,24].

Hemp is also an exceptionally useful source for the production of paper, toilet paper, and tissues. Hemp shives can be successfully used in construction. When mixed with water and lime, they form so-called hempcrete, which absorbs carbon dioxide during the life cycle of the building, making it a carbon-negative construction material. Hempcrete is considered a very good alternative to traditional concrete and standard insulation in construction [25,26]. Additionally, an important and broad topic is the potential use of hemp biomass for biofuel production [27]. Hemp can be used to produce biofuels. Moreover, it can generate a higher yield per hectare compared to other crops, especially when both hemp seed and stem biomass are taken into account [28–32].

In studies on the effect of the hemp vegetation phase and fertilization on the amount of biogas, biomass yield and the content of dry matter increased with the age of the plants up to $12.0 \text{ Mg} \cdot \text{ha}^{-1}$ and 32%, respectively. Nevertheless, no significant differences in biogas production between different fertilization methods were observed [33].

However, numerous studies on hemp cultivation have demonstrated that key agronomic factors—particularly nitrogen fertilization rates, plant density or row spacing, and sowing date—significantly influence the yield and quality of straw and seeds, fiber characteristics, and the concentrations of cannabinoids such as Δ^9 -tetrahydrocannabinol and cannabidiol. Nitrogen is an essential macronutrient required for the proper functioning of plant metabolic processes, including photosynthesis, and plays a pivotal role in regulating growth and biomass productivity. Its bioavailability also significantly influences secondary metabolic pathways, determining the synthesis levels of phytocannabinoids, such as Δ^9 -tetrahydrocannabinol (THC) and cannabidiol (CBD). During the vegetative growth phase, fluctuations in primary metabolism and the availability of macro- and micronutrients can modulate the biosynthesis and accumulation of cannabinoids within plant tissues [34].

The interaction between cultivar and nitrogen (N) application rate was also found to be significant. In a study conducted by Navdeep Kaur et al. [35], two out of five cultivars examined—‘Białobrzskie’ and ‘X-59’—showed no significant response to nitrogen fertilization. Conversely, cultivars ‘Yuma’, ‘NWG-2730’, and ‘IH Williams’ exhibited notable increases in yield within the application range of $168\text{--}280 \text{ kg N ha}^{-1}$. Application of nitrogen also positively influenced the height of plants in the case of four cultivars. The exception was the ‘Białobrzskie’ variety. The highest plant stature was recorded at N rates between 168 and 280 kg ha^{-1} . These results highlight the importance of tailoring nitrogen management strategies to specific cultivar responses. The combined optimization of N input and cultivar selection appears to be a key factor in maximizing both biomass and grain yield potential.

Panday et al. [36] examined the effects of fertilization strategies (control, compost at $60 \text{ Mg} \cdot \text{ha}^{-1}$, blood meal containing 12% N at 112 and $224 \text{ kg} \cdot \text{ha}^{-1}$) and row spacing (19 cm vs. 38 cm) on the yield performance and seed chemical composition of seeds of industrial hemp (cv. ‘Canda’). Narrow row spacing led to increased plant and stem density, resulting in enhanced bast fiber yields. In contrast, wider spacing favored biomass of weed accumulation due to reduced competitive pressure from hemp plants. Principal component analysis revealed that compost application had a more pronounced effect on nutrient availability and heavy metal uptake compared to row spacing or blood meal treatments.

These results underscore the critical role of aligning agronomic practices with environmental conditions to optimize crop productivity. Strategic selection of row spacing and nutrient sources is key to improving hemp yield outcomes, reducing input costs, and mitigating environmental impacts.

The effects of cultivar, sowing date, and row spacing on fiber and seed yield were also investigated. The study evaluated five cultivars, three sowing dates (early April, May, and June), and three row spacings (12.5 , 25 , and 50 cm). The tallest plants were recorded in plots with the narrowest row spacing (12.5 cm), while plants sown at 50 cm spacing exhibited a significantly greater stem diameter compared to those grown at 12.5 cm . The results highlight clear variations in plant height as influenced by sowing date and row spacing. Notably, plants sown in April and May tended to reach greater average heights than those sown in June [37].

Taking the above into account, it is appropriate to undertake research on increasing the yield per hectare for both seeds as the main crop and biomass in order to use them for biofuels production or for other purposes in many branches of the economy.

The aim of this research was to assess the potential of the ‘Henola’ hemp variety depending on mineral fertilization together with sowing date and sowing density in order to increase both straw and hemp seeds yields per unit of cultivation area. Increasing both the number of seeds and biomass per hectare will allow for maximizing profits due to the possibility of using both a high main yield and a large amount of biomass in various branches of the non-food economy.

2. Materials and Methods

2.1. Conducting Field Experiments

Field experiments were conducted at the Institute of Natural Fibers and Medicinal Plants–National Research Institute, at the Stary Sielec Experimental Station (51°39′36.15″ N, 17°08′41.75″ E) in Poland, over three consecutive growing seasons from 2021 to 2023. Firstly, the soil chemical composition was investigated. The experiments were carried out on 30 m² experimental plots, in triplicate, during the growing season for the ‘Henola’ hemp variety, which lasts from April to August. Trials were conducted under rainfed conditions. The atmospheric conditions during each season were characterized using the hydrothermal coefficient of Selyaninov.

In all plots and seasons, the preceding crop was maize. Sowing depth was 2–3 cm, achieved by adjusting the seeder settings.

On the designated experimental site, medium-depth plowing was performed in autumn, followed by harrowing in spring.

Two separate experiments were conducted on these prepared plots:

1. Fertilization experiment

This experiment included five mineral fertilization treatments (in kg·ha^{−1}):

- No mineral fertilization (control);
- 40 P₂O₅ + 80 K₂O;
- P + K + 40 N;
- P + K + 80 N;
- P + K + 120 N.

Phosphorus and potassium doses were consistent across all plots except the control. Nitrogen, in the form of ammonium nitrate, was applied separately to each relevant plot. Fertilizers were applied just before sowing and incorporated into the soil by harrowing. The experiment was conducted on plots sown at the turn of April and May, with a row spacing of 35 cm.

2. Sowing date and row spacing experiment

This experiment tested different sowing dates and row spacings:

- Sowing dates:
 - Mid-April—at the beginning of spring cereal sowing;
 - Late April to early May—at the end of spring cereal sowing;
 - Mid-May—as an aftercrop following winter cereals.

Row spacings (in cm): 20, 35, and 50.

These distances were achieved by adjusting the seeder settings. The applied fertilizer dose was 80 N + 40 P₂O₅ + 80 K₂O (in kg·ha^{−1}).

Hemp seeds and straw were harvested in August. Representative samples of both seeds and straw were collected from each plot in three replications, corresponding to the individual experimental setups.

2.2. Statistical Analysis

To evaluate the influence of the fertilization system on the production of straw and hemp seeds, a linear mixed-effects model was initially fitted to the full dataset in order to assess general treatment effects across variable environmental conditions. Fertilization was treated as a fixed factor, while year and block nested within year were modeled as random effects. Model fitting and evaluation were performed using the ‘lme4’, ‘lmerTest’, and ‘emmeans’ packages in R (version 4.2.2).

The results of the mixed-effects model informed the structure of further year-wise analyses. To evaluate the influence of the fertilization system on the production of straw and hemp seeds, a single-factor variance analysis was carried out for each year using a completely random block arrangement. Before the examination, a Levene’s test was conducted to check the uniformity of variance among groups. The research was conducted over a period of three years.

In the event of finding significant differences for the tested experimental factor, Tukey’s multiple post hoc test was employed to determine the specific group means that differed significantly from each other.

To examine the effect of sowing date (April, late April to May, May) and row spacing (20, 35, 50) on straw and seed yields, as well as their interaction, a two-way analysis of variance was employed. In this experiment, a split-plot design over a two-factor factorial with three levels was conducted. Row spacing was assigned to the main plots, while sowing date was assigned to the sub-plots. The experiment comprised three complete blocks. In instances where the null hypothesis concerning main or interaction effects was rejected, post hoc tests were performed to identify specific pairwise differences.

To categorize the treatments (fertilization methods or the combination of sowing date and row spacing), considering the average values of the observed variables, an assessment (cluster analysis) was carried out using Ward’s method of hierarchical grouping and the measure of Euclidean distance. The cluster count was established following the Ball and Hall [38] criterion for grouping. The resulting data depiction provides an apt portrayal of a collection of cluster centers, with the goal of reducing the sum of squared distances from each data point to its closest cluster center. The examination of the likeness among the observed variables was executed in a comparable manner.

The statistical analyses were performed using the ‘agricolae’, ‘NbClust’ and ‘pheatmap’ packages in the R program (version 4.2.2).

3. Results

3.1. Effects of Fertilization on Hemp Yield

Table 1 presents the soil chemical composition at the beginning of the trials.

Table 1. Soil chemical composition at the beginning of the trials.

Type of Agricultural Use	Soil Agronomic Category	pH	Bulk Density g/dm ³	Soil Salinity g NaCl/dm ^{4.5}	N org. %	C org. %	Available Forms of Minerals in mg/100 g of Soil		
							Phosphorus P ₂ O ₅ Content	Potassium K ₂ O Content	Magnesium Mg Content
arable land	light soil	6.7	1350	0.32	0.105	0.87	43.5	16.7	8.8

The soil had a neutral pH, which is suitable for hemp, so liming was not necessary. Phosphorus, potassium, and magnesium levels were sufficiently high. Organic nitrogen and carbon contents were 0.105% and 0.87%, respectively. These are moderate values, within the range typical for mineral soils.

Table 2 presents weather conditions (average monthly temperature and monthly precipitations) in the locations where field experiments were conducted in 2021–2023. The results were collected for the hemp growing season, i.e., for the months from April to August.

Table 2. Temperature profile during the growing season in years 2021–2023.

Weather Conditions During the Growing Season						
Month	2021		2022		2023	
	Temperature [°C]	Precipitations [mm]	Temperature [°C]	Precipitations [mm]	Temperature [°C]	Precipitations [mm]
April	12.1	37.1	9.2	11.3	7.7	4.2
May	15.2	76.8	16.2	37.4	10.7	77.4
June	17.8	67.3	23.4	17.2	17.4	116.5
July	20.6	92.1	19.2	49	19.9	62.2
August	21.5	18.6	21.1	50.1	21.4	92.4

Additionally, for a better representation of atmospheric conditions on the growth and development of plants the hydrothermal coefficient was characterized during each season (Table 3).

Table 3. The value of the hydrothermal coefficient for each season of cultivation.

Hydrothermal Coefficient			
Month	2021	2022	2023
April	1.0	0.4	0.2
May	1.7	2.1	2.4
June	1.3	0.2	2.2
July	1.5	0.8	1.0
August	0.3	0.8	1.4

The hydrothermal coefficient value: >3—extreme moisture conditions; 2.6–3.0—severe moisture conditions; 2.1–2.5—moisture conditions; 1.7–2.0—moderate moisture conditions; 1.4–1.6—optimum; 1.1–1.3—moderate drought; 0.8–1.0—drought; 0.4–0.7—severe drought; <0.4—extreme drought.

Due to the influence of atmospheric conditions on the growth and development of plants the hydrothermal coefficients were characterized during each season (Table 3).

The data presented in the tables above illustrate the weather conditions under which the experiments were conducted. However, to determine their impact on hemp yields, further research is needed.

To evaluate the general effect of mineral fertilization across variable environmental conditions, a linear mixed-effects model was fitted to the full dataset (Table 2). The fertilization was treated as a fixed effect, while year and block nested within year were modeled as random effects. The model revealed a highly significant effect of fertilization on straw yield ($F_{4,38} = 18.73$; $p < 0.001$; Table 4). Compared to the unfertilized control (reference level), all fertilizer treatments significantly increased straw biomass ($p < 0.05$), with the strongest effect observed for PK + 120 N (estimate = 3.10; $p < 0.001$). The random component associated with year explained considerable variability in straw yield ($\sigma^2 = 1.44$), whereas the block effect nested within year was negligible ($\sigma^2 = 0.00$), supporting the importance of inter-annual differences in treatment response.

For seed yield, the effect of fertilization was marginally non-significant in the overall model ($F_{4,38} = 2.44$; $p = 0.064$), although the highest nitrogen dose (PK + 120 N) resulted in a significant increase relative to the unfertilized control (estimate = 0.40; $p = 0.016$). The model for seed yield also showed a singular fit, with zero variance attributed to the block-within-year random component. This suggests that treatment effects were largely consistent across blocks and years. However, despite the overall stability, the presence

of marginal significance and a small year-level variance ($\sigma^2 = 0.04$) implies that seasonal factors might still influence treatment performance in specific years.

Table 4. Fixed and random effects from the linear mixed-effects model for straw and seed yield of hemp.

Straw Yield					
Fertilizer treatment/Effect	Estimate	SE	df	t	p-value
Intercept (No fertilization-reference)	10.7489	0.7427	2.4807	14.473	0.0019
PK	0.8911	0.3758	38.0	2.371	0.0229
PK + 120 N	3.0978	0.3758	38.0	8.243	5.5×10^{-10}
PK + 40 N	1.7822	0.3758	38.0	4.742	3×10^{-5}
PK + 80 N	1.69	0.3758	38.0	4.497	6.3×10^{-5}
Random variance (Year)	1.4429				
Random variance (Block:Year)	0.0				
Residual variance	0.6355				
Type III ANOVA results using Satterthwaite's method. Fertilization: $F(4; 38) = 18.73$, $p = 1.41 \times 10^{-8}$					
Seed Yield					
Intercept (No fertilization-reference)	2.15667	0.16198	5.04587	13.315	4×10^{-5}
PK	0.02889	0.15712	38.0	0.184	0.8551
PK + 120 N	0.39667	0.15712	38.0	2.525	0.0159
PK + 40 N	0.20222	0.15712	38.0	1.287	0.2059
PK + 80 N	0.31444	0.15712	38.0	2.001	0.0525
Random variance (Year)	0.04168				
Random variance (Block:Year)	0.0				
Residual variance	0.11109				
Type III ANOVA results using Satterthwaite's method. Fertilization: $F(4; 38) = 2.44$, $p = 0.0636$					

SE—standard error; df—degrees of freedom; t—t-statistic. Type III ANOVA results were calculated using Satterthwaite's approximation for degrees of freedom. $F(df_n, df_d)$ —F-statistic with numerator degrees of freedom (dfn) and denominator degrees of freedom (dfd); p —p-value; PK—phosphorus and potassium; N—nitrogen (e.g., PK + 80 N = 80 kg N·ha^{−1} added to PK).

These results indicate that plant response to fertilization, especially for straw production, was influenced by inter-annual environmental variability. Therefore, to clarify year-specific patterns and better understand treatment-by-environment interactions under distinct seasonal conditions, we performed separate one-way ANOVA analyses by year using a randomized block design (see Table 5).

The highest straw yield was observed for hemp plants treated with PK plus 120 N throughout the study. In the third year, the highest mean yield was recorded (15.9 Mg·ha^{−1}). The highest yield in the second year was lower by 4.61 Mg·ha^{−1} (11.29 Mg·ha^{−1}). The mean yield, however, was equal to 10.84 Mg·ha^{−1}, which was lower by 1.94 Mg·ha^{−1} and 2.25 Mg·ha^{−1} compared to the means of the first and third year, respectively (Table 6).

No significant differences in straw yield were detected between the unfertilized and PK treatments in the first two years based on statistical analysis. Moreover, no significant differences were observed between PK and PK + 40 N in the third year. Furthermore, comparing the first two years of the study, the average straw yield for PK + 120 N did not significantly differ from the second-ranked yield for PK + 40 N. However, in the final year, significant differences were found between the highest average straw yield and the yields for other fertilization systems.

Table 5. Analysis of variance for the analyzed traits (straw and seed yield).

Analysis of Variance																
	Df	Sum Sq	Straw Yield—Year I				Sum Sq	Straw Yield—Year II				Sum Sq	Straw Yield—Year III			
			Mean Sq	F value	Pr (>F)			Mean Sq	F value	Pr (>F)			Mean Sq	F value	Pr (>F)	
Fertilization	4	22.586	5.646	55.242	1.74×10^{-6}	***	1.144	0.286	5.110	0.024	*	44.621	11.155	126.945	2.86×10^{-7}	***
Block	2	0.820	0.410	4.010	0.062	.	0.066	0.328	0.587	0.578		0.547	0.274	3.112	0.1	
Residuals	8	0.818	0.102				0.448	0.056				0.703	0.088			
Levene's Test for Homogeneity of Variance																
	4;10		0.083	0.986				0.21	0.927				0.443	0.775		
Analysis of Variance																
	Df	Sum Sq	Seed Yield—Year I				Sum Sq	Seed Yield—Year II				Sum Sq	Seed Yield—Year III			
			Mean Sq	F value	Pr (>F)			Mean Sq	F value	Pr (>F)			Mean Sq	F value	Pr (>F)	
Fertilization	4	1.036	0.259	33.963	4.71×10^{-5}	***	2.624	0.656	251.940	1.91×10^{-8}	***	1.385	0.346	16.587	0.001	***
Block	2	0.007	0.004	0.4743	0.639		0.001	0.000	0.123	0.886		0.003	0.002	0.0719	0.931	
Residuals	8	0.062	0.008				0.021	0.003				0.167	0.021			
Levene's Test for Homogeneity of Variance																
	4;10		0.574	0.688				1.367	0.313				0.048	0.995		

Df—degrees of freedom; Sum Sq—sum of squares; Mean Sq—mean square; F value—F statistic; Pr (>F)—probability value; *** for a significance level of 0.001; * for a significance level of 0.05; . for a significance level of 0.1.

Table 6. Straw and seed yields ($\pm$ std) depending on fertilization doses in three consecutive years. Letters denote groups of means which do not display significant differences (5% significance level) according to the results of post hoc tests.

Straw Yield [Mg·ha ^{−1}]						
	Year I	Groups	Year II	Groups	Year III	Groups
No fertilization	11.063 (± 0.480)	c	10.6 (± 0.265)	b	10.583 (± 0.401)	d
PK	11.687 (± 0.280)	c	10.8 (± 0.1)	ab	12.433 (± 0.340)	c
PK + 120 N	14.35 (± 0.429)	a	11.29 (± 0.208)	a	15.9 (± 0.1)	a
PK + 40 N	13.643 (± 0.407)	ab	11 (± 0.229)	ab	12.95 (± 0.477)	bc
PK + 80 N	13.2 (± 0.4)	b	10.533 (± 0.284)	b	13.583 (± 0.333)	b
Seed Yield [Mg·ha ^{−1}]						
	Year I	Groups	Year II	Groups	Year III	Groups
No fertilization	2.797 (± 0.045)	a	1.59 (± 0.1)	c	2.083 (± 0.1043)	c
PK	2.53 (± 0.111)	b	1.693 (± 0.012)	c	2.33 (± 0.126)	bc
PK + 120 N	2.2 (± 0.036)	cd	2.527 (± 0.093)	a	2.933 (± 0.153)	a
PK + 40 N	2.303 (± 0.116)	bc	2.123 (± 0.031)	b	2.65 (± 0.132)	ab
PK + 80 N	2.047 (± 0.072)	d	2.617 (± 0.031)	a	2.75 (± 0.132)	a

Values are means $\pm$ standard deviation (std). Different letters indicate statistically significant differences (Tukey's test, $p < 0.05$).

In subsequent years, significant differences in hemp seed yield were also observed based on the fertilization system. In the third year of the study, the highest average seed yield was recorded (2.55 Mg·ha^{−1}), while the lowest was recorded in the second year (2.11 Mg·ha^{−1}). The influence of fertilization system on seed yield varied across the study years.

In the second and third years, the highest yields were obtained for PK + 120 N (2.53 Mg·ha^{−1} and 2.93 Mg·ha^{−1}) and PK + 80 N (2.62 Mg·ha^{−1} and 2.75 Mg·ha^{−1}), with no statistically significant differences observed between these yields. In the first year, significantly lower seed yields were observed for these fertilization systems compared to the unfertilized treatment (2.8 Mg·ha^{−1}) and PK treatment (2.53 Mg·ha^{−1}). In the second and third years, no significant differences in hemp seed yield were found for the unfertilized treatment (1.59 Mg·ha^{−1} and 2.08 Mg·ha^{−1}, respectively) and the PK treatment, although the average seed yield in the second year was 0.1 Mg higher and in the third year was 0.25 Mg higher for PK compared to the unfertilized treatment.

In Figure 2, an extended heat map with the results of cluster analysis for fertilization systems regarding straw and seed yields over three years of research is displayed. Due to variations in the measurement values for straw and seed yields, data scaling (z-score) was conducted. The outcomes revealed a mean of 0 for all variables, with the unit of difference

being one standard deviation. Based on the Ball and Hall [38] criterion, there were two main clusters identified for the studied fertilization systems. The highest similarity in terms of yield was observed for PK and NO, where both straw and seed yields were consistently below the overall average across all years. An exception was the seed yield in the first year of the study, when the averages for this cluster were higher than in the case of other fertilization systems. The second cluster includes fertilization with additional doses of N. Within this cluster, systems with the two lower N doses show greater similarity, while the application of PK + 120N results in the highest average yields for most observed variables. However, there is no clear similarity structure for straw and seed yields over the years, suggesting the need for independent inference for each variable.

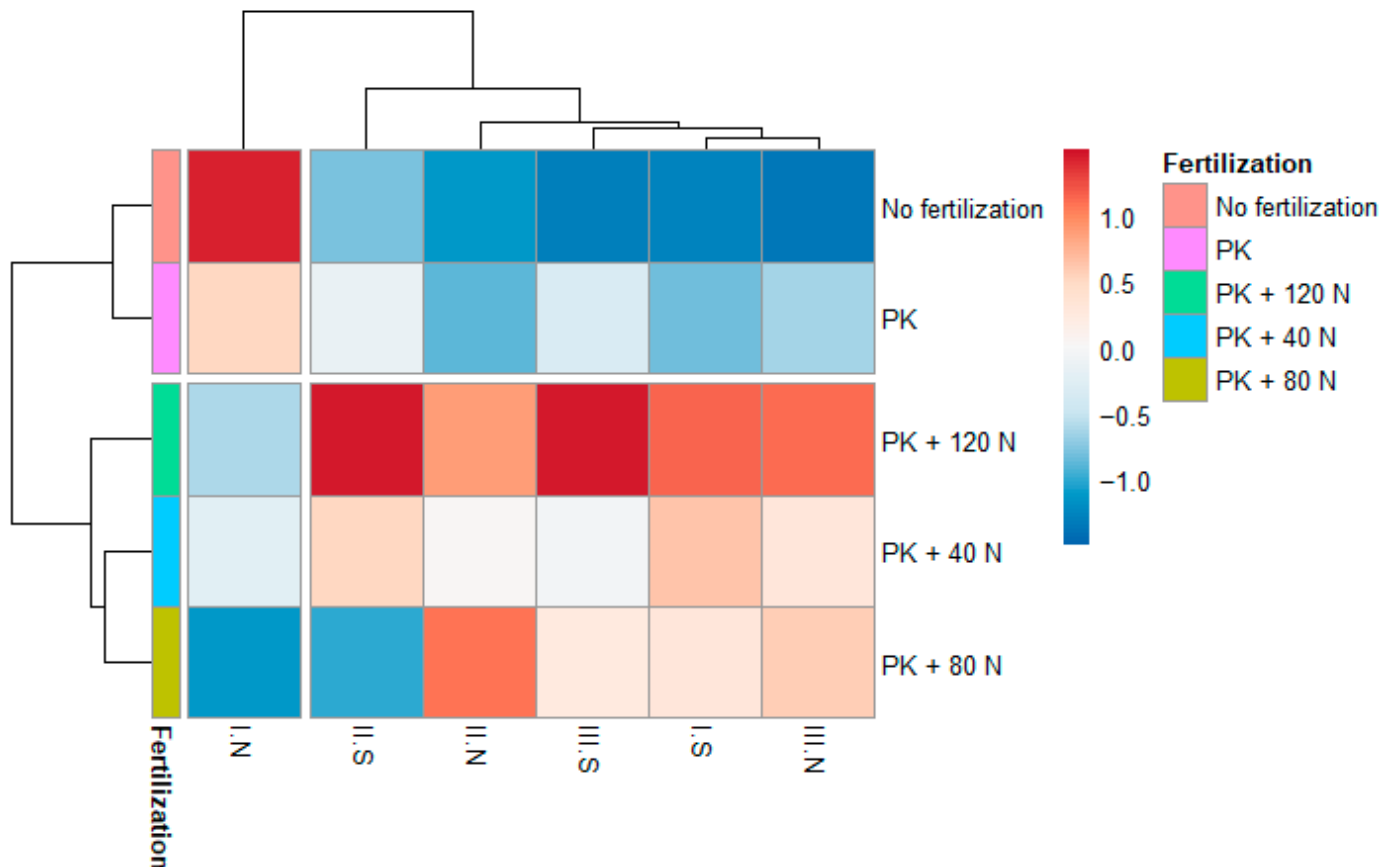


Figure 2. Heat map extended with the results of the cluster analysis. Group analysis was carried out using Ward’s method of grouping and the measure of distance in Euclidean space. The count of groups was established following the Ball and Hall criterion for grouping. Z-score standardization was applied. PK—phosphorus and potassium; N—nitrogen (e.g., PK + 80 N = 80 kg N·ha^{−1} added to PK); Roman numerals (I, II, III) indicate the study year (2021, 2022, 2023, respectively); N—seed yield; S—straw yield.

To further investigate the relationship between seed and straw yield under different fertilization treatments, Pearson’s correlation coefficients were calculated separately for each growing season. In the first year, a strong negative correlation was observed between straw and seed yields ($r = -0.85$, $p = 0.069$), suggesting a possible trade-off between the two traits under varying nitrogen inputs, although the result was not statistically significant at the 0.05 level. In the second year, the correlation was weak and positive ($r = 0.30$, $p = 0.62$), indicating a relatively independent response of seed and straw yield to fertilization treatments during that season. In contrast, the third year exhibited a strong and statistically significant positive correlation ($r = 0.94$, $p = 0.016$), implying that treatments

leading to high straw yield also produced high seed yield. This consistency of response supports the clustering pattern seen in Figure 2, where the PK + 120 N treatment consistently formed a distinct group with the highest yields in both categories. These results confirm that the relationship between seed and straw yields is variable across years and may depend on environmental conditions or specific treatment interactions. Furthermore, the absence of a uniform correlation pattern in the first two years aligns with the heatmap structure in Figure 2, where the grouping of treatments with lower nitrogen doses (PK and PK + 40 N) shows less consistent yield behavior across seasons. In contrast, the third-year results show a converging pattern in both the correlation and the cluster structure, highlighting the stabilizing effect of high nitrogen fertilization (PK + 120 N) on dual-yield performance.

3.2. Influence of Sowing Date and Row Spacing on Straw and Seed Yield

A statistical analysis was also carried out for straw and seed yield depending on the date of sowing and the width of the rows (Table 7).

Table 7. Analysis of variance of hemp straw and seed yield in relation to sowing date and row spacing.

Analysis of Variance—Straw Yield															
Year I						Year II					Year III				
	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Df	Sum Sq	Mean Sq	F value	Pr (>F)
BLOCK	2	0.682	0.341			2	0.117	0.058			2	0.124	0.062		
SPACING	2	1.499	0.750	5.922	0.064	2	0.191	0.096	0.858	0.490	2	5.363	2.681	14.598	0.015
Ea	4	0.506	0.127			4	0.446	0.112			4	0.735	0.184		
DATE	2	9.680	4.840	28.651	2.70×10^{-5}	2	0.272	0.136	0.599	0.565	2	3.783	1.892	6.479	0.0124
SPACING; DATE	4	0.039	0.010	0.058	0.993	4	0.420	0.105	0.462	0.763	4	8.345	2.086	7.146	0.003
Eb	12	2.027	0.169			12	2.726	0.227			12	3.504	0.292		**
Analysis of Variance—Seed Yield															
Year I						Year II					Year III				
	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Df	Sum Sq	Mean Sq	F value	Pr (>F)
BLOCK	2	0.022	0.011			2	0.063	0.032			2	0.051	0.025		
SPACING	2	0.035	0.018	1.569	0.314	2	0.495	0.248	4.496	0.095	2	0.395	0.197	10.568	0.025
Ea	4	0.045	0.011			4	0.220	0.055			4	0.075	0.019		*
DATE	2	5.121	2.561	451.58	5.083×10^{-12}	2	8.091	4.045	77.735	1.354×10^{-7}	2	1.104	0.552	41.861	3.88×10^{-6}
SPACING; DATE	4	8.40×10^{-2}	0.021	3.702	3.47×10^{-2}	4	0.321	0.080	1.542	0.2523	4	0.043	0.011	0.816	0.539
Eb	12	0.068	0.006			12	0.625	0.052			12	0.158	0.013		12

Df—degrees of freedom; Sum Sq—sum of squares; Mean Sq—mean square; F value—F statistic; Pr (>F)—probability value; *** for a significance level of 0.001; ** for a significance level of 0.01; * for a significance level of 0.05; . for a significance level of 0.1.

The analysis of hemp straw yield in relation to sowing date and row spacing showed that there were significant differences in yield based on sowing date in the third year of the study.

Table 8 shows the yield of straw and seeds depending on the date of sowing and the width of the rows.

The highest straw yield was obtained for sowing in late April and May ($14.35 \text{ Mg} \cdot \text{ha}^{-1}$), which differed significantly from the straw yields obtained for April ($13.6 \text{ Mg} \cdot \text{ha}^{-1}$) and May ($12.88 \text{ Mg} \cdot \text{ha}^{-1}$) sowings. However, there were no significant differences observed for row spacing. The highest average yield was observed for a row spacing of 35 ($13.94 \text{ Mg} \cdot \text{ha}^{-1}$), which was $0.41 \text{ Mg} \cdot \text{ha}^{-1}$ and $0.55 \text{ Mg} \cdot \text{ha}^{-1}$ higher compared to the yields for row spacings of 0.2 and 0.5 m, respectively.

Table 8. Straw and seed yields depending on sowing data and row spacing in three years. Letters denote groups of means which do not display significant differences (5% significance level) according to the results of post hoc tests.

Straw Yield [Mg·ha ^{−1}]															
Year I Row Spacing					Year II Row Spacing					Year III Row Spacing					
Date	20	35	50	Mean	Date	20	35	50	Mean	Date	20	35	50	Mean	
IV	13.45	13.92	13.46	13.62	IV	13.25	13.63	13.14	13.34	IV	19.39	a	17.6	ab	16.78
IV/V	14.29	14.7	14.06	14.35	IV/V	13.42	13.72	13.59	13.58	IV/V	18	ab	16.92	b	16.91
V	12.81	13.21	12.63	12.88	V	13.38	13.31	13.53	13.40	V	16.65	b	17.28	b	17.16
Mean	13.53	13.94	13.39		Mean	13.35	13.55	13.42		Mean	18.01		17.27	16.95	

Seed Yield [Mg·ha ^{−1}]															
Year I Row Spacing					Year II Row Spacing					Year III Row Spacing					
Date	20	35	50	Mean	Date	20	35	50	Mean	Date	20	35	50	Mean	
IV	1.53	b	1.45	bc	1.40	bc	1.46			IV	2.67	2.52	2.29	2.49	a
IV/V	2.13	a	2.28	a	2.24	a	2.22			IV/V	2.37	2.15	2.15	2.22	b
V	1.25	cd	1.23	cd	1.07	d	1.19			V	2.14	2.01	1.85	2.00	c
Mean	1.64	1.65	1.57		Mean	2.02	1.8	1.70		Mean	2.39	a	2.23	ab	2.10

Values are means. Different letters indicate statistically significant differences (Tukey's test, $p < 0.05$). Date: IV—mid-April; IV/V—late April to early May; V—mid-May. Row spacing: 20 = 0.2 m, 35 = 0.35 m, 50 = 0.5 m.

In the first two years of the study, the highest straw yield was obtained for sowing in late April and May and a row spacing of 0.35 m, with yields of 14.7 Mg·ha^{−1} in the first year and 13.72 Mg·ha^{−1} in the second year. The lowest average yields in these years were recorded for May sowing and a row spacing of 0.5 m, with yields of 12.63 Mg·ha^{−1} and 13.14 Mg·ha^{−1}, respectively. The second year displayed similar characteristics as the first year. The highest average yield was obtained for sowing in late April and May, whilst the lowest yield was observed for April sowing. However, no significant differences were found between these two sowing dates. Additionally, in this year, a row spacing of 0.35 m proved to be the most beneficial for straw yield, with an average yield of 13.55 Mg·ha^{−1}.

However, in the last year of study, a significant interaction between sowing date and row spacing was observed. The highest average straw yield was obtained for the smallest row spacing and April sowing (19.39 Mg·ha^{−1}), which did not significantly differ from the yield for late April and May sowing with the same row spacing, as well as from the April yield with a row spacing of 0.35 m. Conversely, the lowest average yield was obtained for May sowing and a row spacing of 0.2 m, which was 2.73 Mg·ha^{−1} lower than the yield for April sowing with the same row spacing.

In terms of seed yield, a significant interaction between sowing date and row spacing was observed in the first year of the study. The highest hemp seed yield was obtained for a row spacing of 0.35 m and sowing in late April and May (2.27 Mg·ha^{−1}), with no significant differences observed between this experimental combination and late April and May sowing with smaller row spacings. For the remaining experimental combinations, the average yield was lower, ranging from 1.54 Mg·ha^{−1} to 1.07 Mg·ha^{−1} for May sowing with the largest row spacing. In the second year of the study, no significant differences were found for row spacing or the interaction between row spacing and sowing date. The statistically significant factor was the sowing date. The highest average yields were obtained for sowing in late April and May, with yields of 2.47 Mg·ha^{−1}. Seed yield for April sowings was 0.56 Mg·ha^{−1} lower than for the transitional months, and for May sowings, it was even 1.34 Mg·ha^{−1} lower. In the second year of the study, a decrease in yield was observed with increasing row spacing, but these differences were not statistically significant. The highest-yielding experimental combination in the second year (2.63 Mg·ha^{−1}) was a row spacing of 0.2 m and sowing in the transitional months, while the lowest yield was obtained for May sowing and a row spacing of 0.5 m (0.997 Mg·ha^{−1}). In the last year of the study, significant differences were observed for both experimental factors, but no interaction was found. The highest average yield was observed for the smallest row spacing (2.39 Mg·ha^{−1}), which did not differ significantly from the yield for a row spacing of 0.35 m,

but it differed significantly from the yield for a row spacing of 0.5 m, which was 0.296 Mg lower. The optimal sowing date in the third year of the study was in April, with an average yield of 2.49 Mg·ha⁻¹, which was 0.49 Mg·ha⁻¹ and 0.27 Mg·ha⁻¹ higher than the average yield for May sowing and sowing in the transitional months, respectively.

Figure 3 displays a heat map incorporating cluster analysis results for sowing dates and row spacing concerning straw and seed yields over three years of research. To account for variations in measurement values, data scaling (z-score) was performed. According to the Ball and Hall criterion [38], three main clusters were identified for the studied sowing dates and row spacing systems. The highest similarity in terms of yield was observed for R 50 T IV and all spacings covered in May (R 50 T V, R 20 T V and R 35 T V). Both straw and seed yields were consistently below or equal to the overall average in all years of study, except for three occurrences. One exception occurred in the third year, whilst the other two occurred in the second year. There, straw and seed yields were slightly above average. The second cluster consists of terms with sowing date IV–V. Within this cluster, yields in the first two years of study were mostly above average, except for one term. Terms in the third year had values that were equal to or varied minimally from the average. Lastly, the third cluster displayed no clear similarity structure for straw and seed yield over the years. The similarity structure of straw and seed yields over the years is delineated by two primary clusters corresponding to the years of research.

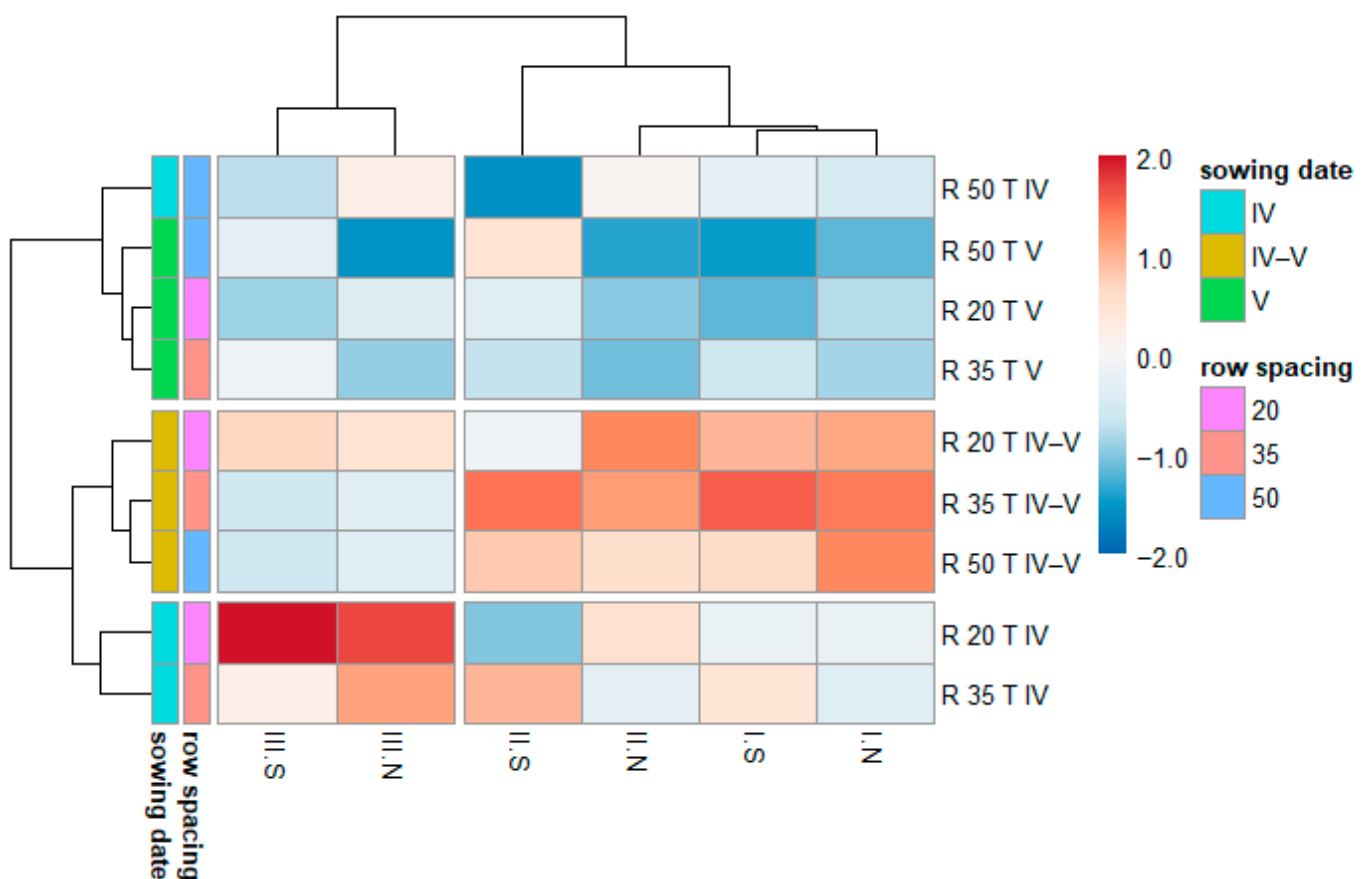


Figure 3. Heat map extended with the results of the cluster analysis. Group analysis was carried out using Ward's method of grouping and the measure of distance in Euclidean space. The count of groups was established following the Ball and Hall criterion for grouping. Z-score standardization was applied. R—row spacing (in cm); T—sowing time (IV = April, IV-V = late April-May, V = May). Roman numerals (I, II, III) indicate the study year (2021, 2022, 2023, respectively); N—seed yield; S—straw yield.

In addition, correlation analysis was also performed for the combinations of sowing date and row spacing. In the first year, a very strong positive correlation was found ($r = 0.91$, $p < 0.001$), suggesting that treatments increasing straw yield also strongly improved seed yield. In the second year, this correlation was weak and statistically insignificant ($r = 0.19$, $p = 0.62$). The third year again showed a strong and statistically significant positive correlation ($r = 0.71$, $p = 0.031$). These results are reflected in the cluster structure seen in Figure 3. In particular, combinations such as R 20 T IV and R 35 T IV–V, which exhibited both high straw and seed yield, grouped together in higher-yield clusters. Meanwhile, the lowest-yielding combinations, such as R 50 T V and R 20 T V, were consistently separated into a distinct cluster with below-average performance. Thus, the correlation analysis confirms and explains the cluster-based grouping of treatments, reinforcing the conclusion that sowing time and row spacing interact to influence both yield components in a coordinated way.

4. Discussion

Undoubtedly, the quantity and quality of the crop is determined by the balance of nutrients supply. Hemp generally responds well to mineral and organic fertilization [39,40]. There are many articles on the impact of mineral fertilization on yield, but they refer to higher varieties of the fibrous type of hemp [41,42]. Moreover, in other species, some studies have noted the impact of fertilization on the bioactive compounds content [43–45].

Previous research on fibrous varieties investigated the effect of fertilization with N, P and K on the biomass and seed yields of hemp. In the case of ‘Anka’ and ‘CRS-1’ hemp varieties, for the following doses of fertilization: 0, 50, 100, 150, 200 N kg·ha^{−1} or K kg·ha^{−1} and 0, 25, 50, 75, 100 P kg·ha^{−1}, biomass and seed yields ranged from 1674 to 4209 kg·ha^{−1} and from 519 to 1340 kg·ha^{−1}, respectively, with addition of 200 N kg·ha^{−1} in the control region. While the biomass and seed yields of these two industrial hemp cultivars responded positively to N fertilization, the response to P and K fertilization was insignificant [46]. In another experiment increasing doses of nitrogen fertilization had a positive impact on hemp biomass yield, i.e., a 37.3% increase for 240 N kg·ha^{−1} compared with the control [47].

Research was also carried out on the ‘Henola’ cultivar with the use of organic fertilization in the form of *Bombyx mori* L. excrement, which is a waste product in insect breeding. The silkworm waste is rich in N: 36–47%, Ca: 0.5–4%, P: 0.2–0.8%, and contains trace elements (in mg·kg^{−1}), such as Cu: 8.0–12.5, Mn: 87.17, Fe: 1962–2560, Zn: 43.8, and Pb: 5.93. The results of this experiment showed the biomass yield significantly increased when organic fertilization was applied, especially compared to the unfertilized control sample [35].

In studies on mineral fertilization conducted in the USA on Polish hemp varieties, including the ‘Henola’ variety, the application of fertilization in the amount of 146.5 kg·ha^{−1} (130 lb·acre^{−1}) increased the ‘Henola’ biomass yield by over 50%, and the seed yield by almost 50% in non-irrigated experiments and by 30 and 26%, respectively, in the irrigated experiment compared to the non-nitrogen-fertilized control. Similar results were obtained in the present study conducted on an oil-type hemp variety. The highest yield of straw was recorded with a high dose of nitrogen fertilization, and no significant differences were noted with P and K fertilization comparing to the control. Also, the yield of seeds was the highest at the two highest doses of nitrogen fertilization (PK + 120 N and PK + 80 N). All the studies cited indicate a significant positive response of hemp to nitrogen fertilization [35,46]. Nevertheless, based on the research on the possibility of hemp biomass usage for energy purposes, the Prade team concluded that the level of nitrogen fertilization may be less important for the yield than the date of sowing. However, it was noted that this topic requires further research [47].

The year-specific analysis revealed several unexpected patterns in our own study. In Year I, seed yield in the unfertilized control was the highest among treatments (mean $2.23 \text{ Mg}\cdot\text{ha}^{-1}$), surpassing even nitrogen-fertilized plots (Table 5). This observation is consistent across replicates and was statistically supported by the post hoc test, indicating that in this particular season, the crop's performance was not limited by external nitrogen inputs. According to the climatic records for that year, early and uniform rainfall as well as moderate temperatures may have promoted the mineralization of organic nitrogen or improved nutrient uptake efficiency in control plots. Similar mechanisms could not be verified without additional soil data, but the effect was not reproducible in subsequent years.

In Year III, under the sowing date experiment, seed yield was highest for the latest sowing date (VI/V), independently of row spacing (Table 4). The three highest-yielding treatments (35: IV–V, 50: IV–V, 20: IV–V) all belonged to this group and were statistically indistinguishable (group “a”). This suggests that, in this specific year, delayed sowing may have coincided with more favorable temperature or moisture conditions during flowering and seed setting. However, this effect likely reflects seasonal conditions rather than agronomic treatment per se.

5. Conclusions

This study demonstrated that both fertilization and sowing practices significantly affect the straw and seed yields of the monoecious hemp cultivar ‘Henola’. High nitrogen doses (PK + 120 N) consistently led to the highest yields. The optimal sowing period was late April to early May, with narrower row spacings (0.2 m and 0.35 m) favoring seed yield. Correlation analyses showed strong alignment between seed and straw yield responses in certain years, particularly under high-input conditions, and were consistent with cluster analysis groupings. These findings support targeted agronomic recommendations to optimize hemp production for different end uses.

The primary aim of this research was to determine optimal agronomic practices that would increase both seed and straw yield in ‘Henola’ hemp through the adjustment of mineral fertilization, sowing date, and row spacing. The results confirmed that elevated nitrogen inputs boost productivity, and early sowing enhances yield potential, particularly in favorable seasons.

This work contributes to the body of knowledge by establishing yield-maximizing combinations for seed and straw production in monoecious hemp under central European climatic conditions, particularly for the ‘Henola’ cultivar. Notably, the results highlight the consistent benefits of high nitrogen supply, while the effect of row spacing varied by year. However, limitations such as inter-annual climatic variability and non-irrigated conditions may have influenced treatment responses, highlighting the need for broader environmental validation.

Further investigations are necessary to determine the impact of atmospheric factors on hemp yield. Incorporating these findings into cultivation guidelines will improve agronomic decision-making and promote sustainable hemp production for various purposes.

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Abbreviations

The following abbreviations are used in this manuscript:

P₂O₅ Diphosphorus pentoxide
K₂O Potassium oxide

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