

YIELD, QUALITY AND PHYSIOLOGICAL TRAITS OF MONOECIOUS HEMP (*Cannabis sativa* L.) AS INFLUENCED BY SOWING TIME AND FERTILIZATION

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Abstract

Hemp is gaining increasing interest due to its high yield potential and multiple uses. This study was conducted under field conditions at ARDS Secuieni to assess the influence of sowing time and fertilization on yield performance, physiological traits, and biochemical quality of an early monoecious hemp variety, using a bifactorial split-plot experimental design. The E1 × F1 combination enhanced vegetative biomass accumulation, resulting in the highest inflorescence biomass (5300 kg·ha⁻¹ fresh and 1600 kg·ha⁻¹ dry) and stem yield (4380 kg·ha⁻¹), whereas seed production reached its maximum under the E1 × F2 combination (3293 kg·ha⁻¹). The second sowing time (E2) was associated with the highest photosynthetic rate (14.5 μmol CO₂·m⁻²·s⁻¹) and the greatest amount of carbon stored in the soil (68.3 t·ha⁻¹), while F1 fertilization recorded the highest photosynthetic rate (15.5 μmol CO₂·m⁻²·s⁻¹). Moreover, the interaction between the second sowing time and F1 fertilization maximized vitamin C content (67.3 mg·100 g⁻¹) and soluble solids (12.3 °Brix). Overall, the results highlight the importance of appropriate sowing time and fertilization in improving productivity and quality in monoecious hemp.

Key words: inflorescence biomass, stem yield, seed yield, photosynthetic rate, biochemical traits.

INTRODUCTION

Cannabis sativa L., commonly known as industrial hemp, is one of the oldest cultivated plants in human history originating from Central Asia, with documented uses spanning thousands of years across diverse civilizations (Rupasinghe et al., 2020). In recent decades, however, hemp has experienced a remarkable renaissance in agricultural research and commercial cultivation, driven by growing recognition of its extraordinary versatility and its potential to contribute to more sustainable agricultural systems (Struik et al., 2000). The plant is capable of producing a wide range of valuable outputs, including fiber, seeds, oil, and bioactive compounds, making it one of the most multi-purpose crops available to modern

agriculture (Naeem et al., 2023).

From an agronomic perspective, hemp is particularly valued for its rapid growth rate, high biomass production capacity, and relatively low input requirements compared to other industrial crops (Matvejeva et al., 2026). The deep root system of hemp contributes to improving soil structure, while its vigorous growth and dense crop stand effectively suppress weed development, thereby reducing the need for herbicide applications. Hemp is a particularly beneficial crop for soil organic carbon (SOC) accumulation, as its extensive root biomass penetrates deeper soil layers, contributing to long-term carbon sequestration. Furthermore, hemp has been recognized for its capacity to accumulate and sequester carbon both in aboveground biomass and soil organic matter

(Chimento and Amaducci, 2015; Adesina et al., 2020). Soil organic carbon stock is an increasingly important indicator for evaluating the environmental sustainability of cropping systems, as it reflects the capacity of agricultural soils to store carbon and maintain long-term fertility (Nwaogu et al., 2026).

Based on the distribution of floral sexes, industrial hemp can be classified into dioecious and monoecious forms. Monoecious cultivars are particularly valued in breeding programs and commercial production due to their more uniform maturation and greater compatibility with mechanized harvesting (Habán et al., 2022; Ona et al., 2025).

The quality of agricultural production is influenced by the interaction of multiple factors, including genotype, environmental conditions, and crop management practices (Agapie and Sala, 2022).

Sowing time is a critical determinant of crop performance, as it directly influences the photoperiodic and thermal conditions experienced during key developmental stages, including vegetative growth, flowering, and seed formation. Inappropriate sowing dates may expose crops to unfavorable environmental conditions, resulting in reduced yields, altered biochemical composition, and decreased physiological efficiency. Conversely, appropriately timed sowing synchronizes crop development with favorable climatic conditions, thereby maximizing productivity and quality (Butkevičienė et al., 2021).

Within crop management technologies, fertilization plays a key role in determining both the level and the quality of agricultural production (Agapie and Sala, 2023), as nutrient availability, particularly nitrogen, is considered one of the main factors limiting crop productivity worldwide (Agapie et al., 2023). In the case of hemp, fertilization is also an important factor influencing crop yield and quality. Nitrogen, in particular, plays a central role in stimulating vegetative growth and biomass accumulation, while organic and humic-based fertilizers have been increasingly investigated for their capacity to improve soil biological activity, enhance nutrient use efficiency, and support root development (Teliban et al., 2020, 2022). The growing interest in sustainable agriculture has stimulated

research into the use of biostimulants and organic fertilizers as alternatives or complements to conventional synthetic inputs, with promising results reported for various crops, including hemp (Da Cunha Leme Filho et al., 2024).

Given this background, the present study was conducted under field conditions at the Agricultural Research and Development Station Secuieni, Romania, to evaluate the effects of two sowing times and three fertilization treatments on yield performance, biochemical quality traits, photosynthetic activity, and soil carbon storage in the monoecious hemp variety Secuieni-Jubileu. The study aimed to identify suitable combinations of sowing time and fertilization in order to optimize both the quantitative and qualitative performance of the crop and to contribute to the development of agronomic recommendations for monoecious hemp production under temperate continental conditions, particularly in the context of current climate change.

MATERIALS AND METHODS

Experimental Location and Design

The research was carried out in 2025 at the experimental field of the Agricultural Research and Development Station (ARDS) Secuieni, Neamț County. The study was organized as a bifactorial experiment, arranged in a split-plot design with three replications.

The experimental factors considered in the study were: A = sowing time [a_1 – sowing time I (first decade of May); a_2 – sowing time II (second decade of May)] and B = fertilization treatment (b_1 – non-fertilized control; b_2 – fertilized with PromoStart®; b_3 – fertilized with Terrenova®). The experimental plot had an area of 40 m² and was sown with a mechanical seeder at a row spacing of 70 cm. At harvest maturity, the crop density was 7-8 plants·m⁻².

The soil of the experimental field was characterized by a high content of nitrogen, phosphorus, and potassium, as well as adequate levels of magnesium, sulfur, iron, copper, and zinc, providing favorable nutritional conditions for hemp crop development. The moderate humus and organic carbon content contributed to maintaining soil structure and good water retention capacity. The soil reaction was slightly

acidic (pH = 6.72), with no salinity issues recorded.

Biological Material

The biological material used in the study was the monoecious hemp variety Secuieni-Jubileu, developed and homologated in 2012 at the Agricultural Research and Development Station Secueni.

Fertilizers used

PromoStart® is a controlled-release nitrogen-based fertilizer used for foliar application, which stimulates vegetative growth and supplies available nitrogen to plants. Its composition includes total nitrogen (30.0%), urea nitrogen (5.0%), and formaldehyde nitrogen (25.0%).

Terrenova® is an organic fertilizer based on humic and fulvic acids, intended to improve soil fertility and stimulate root system development. It contains total humic extract (18.2%), humic acids (9.1%), fulvic acids (9.1%), potassium (11.4%), free amino acids (5.7%), phosphorus (5.7%), and total nitrogen (0.91%).

Fertilizers were applied in three stages, at the beginning, middle, and end of the flowering phase, at rates of 8 L·ha⁻¹ for PromoStart® and 10 L·ha⁻¹ for Terrenova®.

The meteorological conditions during the experimental period, namely air temperature and precipitation, are presented in Figures 1 and 2.



Figure 1. Multi-year and monthly average temperature (°C)

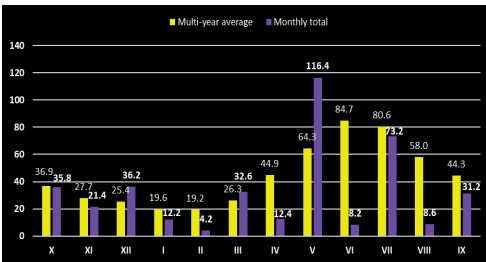


Figure 2. Multi-year and monthly total precipitations (mm)

Measurements and Analyses

The measurements aimed to evaluate seed and biomass production (stems, inflorescences - fresh yield and inflorescences - dry yield). Biochemical and physiological traits were also assessed, including vitamin C content, total soluble solids (TSS), photosynthetic rate, and soil organic carbon stock.

Ascorbic acid content (vitamin C) was determined reflectometrically using the Reflectoquant™ system (RQflex® 20, Merck KGaA), following extraction in a 1% oxalic acid stabilizing solution.

Total soluble solids (TSS) were determined using a Zeiss refractometer, with results expressed in °Brix according to OECD standards (2018).

Leaf gas exchange parameters were measured using the portable photosynthesis system LCpro T® (ADC BioScientific Ltd., UK). The photosynthetic rate was expressed in μmol CO₂·m⁻²·s⁻¹.

Soil organic carbon (SOC) content (%) was determined according to SR ISO 10694:1998 using a Vario MICRO Cube elemental analyzer. Soil organic carbon stock (SOCS) was calculated according to the formula proposed by Pearson and Buraka (Pearson et al., 2005; Buraka et al., 2022):

$$SOCS = BD \times D \times \%C$$

where: SOCS (t·ha⁻¹) represents the soil organic carbon stock, BD (g·cm⁻³) is the soil bulk density, D (cm) is the soil depth, and %C represents the soil organic carbon concentration expressed as percentage.

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) for bifactorial experiments. Differences between means were evaluated using Tukey's test at a significance level of $p < 0.05$.

To highlight the relationships among the analyzed variables and to reduce the dimensionality of the dataset, Principal Component Analysis (PCA) was applied. Correlations among the parameters studied were determined using the Pearson correlation coefficient in Origin ProLab 2026 free trial.

Table 1. Influence of sowing time and fertilization on biomass and seed yield in hemp crop

Variant	Fresh inflorescence yield (kg·ha ⁻¹)	Dry inflorescence yield (kg·ha ⁻¹)	Stems yield (kg·ha ⁻¹)	Seed yield (kg·ha ⁻¹)
Sowing time				
E1	4867 ± 108	1467 ± 26	4193 ± 123	3152 ± 17
E2	4650 ± 36	1383 ± 23	3961 ± 59	2772 ± 37
<i>Significance</i>	<i>ns</i>	<i>ns</i>	*	*
Fertilization				
NF	4150 ± 33 b	1275 ± 40 b	3943 ± 53	2782 ± 49 b
F1	5225 ± 230 a	1575 ± 4 a	4318 ± 142	2948 ± 41 b
F2	4900 ± 104 a	1425 ± 49 ab	4188 ± 64	3157 ± 39 a
<i>Significance</i>	*	*	<i>ns</i>	*

E1 - sowing time I, E2 - sowing time II, NF - non-fertilized control, F1 - fertilized with PromoStart®, F2 - fertilized with Terrenova®;

Values are presented as mean ± standard error (SE). Within each column, ns - no statistically significant difference, * - statistically significant difference, values associated to different letters are significantly different according to Tukey's test at $p < 0.05$.

RESULTS AND DISCUSSIONS

The influence of sowing time and fertilization treatment on biomass and seed yield of hemp is presented in Table 1.

Regarding sowing time, the E1 variant recorded significantly higher stems and seed yields compared to E2, with increases of approximately 6.0% and 13.7%, respectively. Fresh and dry inflorescence yields did not show statistically significant differences between the two sowing epochs.

A management strategy aimed at reducing inputs while maintaining adequate yield levels can be achieved by optimizing the sowing time, with the optimal choice depending on the specific production objectives, such as higher seed or biomass yields (Cosentino et al., 2012). Regarding fertilization, both F1 and F2 significantly outperformed the non-fertilized control (NF) for fresh inflorescence yield (+26.0%, +18.1%, respectively) and dry inflorescence yield (+23.5%, +11.8%, respectively). For seed yield, only F2 produced a statistically significant increase over NF (+13.5%). Stems yield was not significantly affected by fertilization treatment.

Nitrogen from fertilizers should be applied in appropriate amounts, as both excess and deficiency can negatively affect crops and the environment. Nitrogen fertilization influences hemp seed and biomass yields to a greater extent than phosphorus and potassium fertilization, particularly under field conditions (Deng et al., 2019; Bruce et al., 2022; Kaur et al., 2023).

The interaction between sowing time and fertilization significantly influenced fresh and dry inflorescence yield and seed yield, while stems yield was not significantly affected (Table 2). E1 × F1 recorded the highest fresh (5300 kg·ha⁻¹, +34.2%) and dry inflorescence yield (1600 kg·ha⁻¹, +33.3%) compared to the lowest-performing E2 × NF combination. Seed yield peaked under E1 × F2 (3293 kg·ha⁻¹), exceeding E2 × NF by 29.6% and E2 × F1 by 19.4%. The E2 × NF combination consistently recorded the lowest values across all yield components, confirming that delayed sowing without fertilization is the least favorable for hemp productivity.

The combination of early May sowing and appropriate fertilization can enhance both yield and crop quality, as also highlighted in the study conducted by Caplan (Caplan et al., 2017).

Table 2. Influence of the interaction between sowing time and fertilization on biomass and seed yield in hemp crop

Variant	Fresh inflorescence yield (kg·ha ⁻¹)	Dry inflorescence yield (kg·ha ⁻¹)	Stems yield (kg·ha ⁻¹)	Seed yield (kg·ha ⁻¹)
E1 x NF	4350 ± 247 ab	1350 ± 119 ab	3997 ± 62	3023 ± 37 abc
E1 x F1	5300 ± 212 a	1600 ± 14 a	4380 ± 231	3140 ± 56 ab
E1 x F2	4950 ± 136 ab	1450 ± 121 ab	4203 ± 93	3293 ± 62 a
E2 x NF	3950 ± 309 b	1200 ± 68 b	3890 ± 130	2540 ± 67 d
E2 x F1	5150 ± 428 ab	1550 ± 19 ab	4257 ± 99	2757 ± 30 cd
E2 x F2	4850 ± 185 ab	1400 ± 55 ab	4173 ± 43	3020 ± 76 bc
<i>Significance</i>	*	*	<i>ns</i>	*

E1 - sowing time I, E2 - sowing time II, NF - non-fertilized control, F1 - fertilized with PromoStart®, F2 - fertilized with Terrenova®;

Values are presented as mean ± standard error (SE). Within each column, ns - no statistically significant difference, * - statistically significant difference, values associated to different letters are significantly different according to Tukey's test at $p < 0.05$.

Table 3 presents the effect of sowing time and fertilization on vitamin C content and total soluble solids (TSS) in monoecious hemp. Both factors produced statistically significant differences ($p < 0.05$) for both parameters. The superiority of the second sowing epoch (65.61 mg/100 g) compared to the first epoch can be attributed to the increased solar radiation intensity and higher temperatures during the vegetation period.

In plant physiology, ascorbic acid acts as a primary protective agent against photo-oxidative stress. According to Smirnov, vitamin C synthesis is directly stimulated by photon flux, functioning as an essential protective mechanism of the photosynthetic apparatus (chloroplasts) against reactive oxygen species (ROS) (Smirnov, 2018).

Regarding fertilization treatment, it also influenced the vitamin C content of the fresh biomass. The average values ranged from 61.58 mg/100 g (non-fertilized control, NF) to 66.17 mg/100 g (F1), indicating a high antioxidant potential of the fresh biomass. The F1 variant represented the optimal accumulation threshold, while the slight decrease observed in the F2 variant (65.00 mg/100 g) suggests the occurrence of a possible “dilution effect”. As reported by Gallie, Lee and Kader, higher levels of fertilization, particularly those associated with nitrogen supply, may stimulate vegetative growth and water accumulation in plant tissues, which can lead to a relative decrease in the concentration of bioactive compounds when expressed on a fresh weight basis (Gallie, 2013; Lee and Kader, 2000).

Table 3. Influence of sowing time and fertilization on biochemical traits of hemp

Variant	Vitamin C (mg/100 g fresh product)	TSS (°Brix)
Sowing time		
E1	62.89 ± 0.24	10.80 ± 0.20
E2	65.61 ± 0.20	11.83 ± 0.05
<i>Significance</i>	*	*
Fertilization		
NF	61.58 ± 0.22 c	11.55 ± 0.05 ab
F1	66.17 ± 0.22 a	11.77 ± 0.37 a
F2	65.00 ± 0.14 b	10.63 ± 0.07 b
<i>Significance</i>	*	*

E1 - sowing time I, E2 - sowing time II, NF - non-fertilized control, F1 - fertilized with PromoStart®, F2 - fertilized with Terrenova®; Values are presented as mean ± standard error (SE). Within each column, * - statistically significant difference, values associated to different letters are significantly different according to Tukey's test at $p < 0.05$.

According to Table 4, the interaction between sowing time and fertilization produced

statistically significant effects ($p < 0.05$) on vitamin C content and total soluble solids (TSS). The E2 × F1 combination recorded the highest values for both parameters, representing an increase of approximately 12.9% in vitamin C content and 13.4% in TSS compared to the E1 × NF combination. The elevated levels of soluble solids in the second sowing epoch suggest enhanced carbon assimilation efficiency, favored by the higher temperatures during the vegetation period.

Table 4. Influence of the interaction between sowing time and fertilization on biochemical traits of hemp

Variant	Vitamin C (mg/100 g fresh product)	TSS (°Brix)
E1 x NF	58.67 ± 0.33 c	10.87 ± 0.07 bc
E1 x F1	65.00 ± 0.29 b	11.20 ± 0.70 abc
E1 x F2	65.00 ± 0.29 b	10.33 ± 0.07 c
E2 x NF	64.50 ± 0.29 b	12.23 ± 0.09 ab
E2 x F1	67.33 ± 0.17 a	12.33 ± 0.07 a
E2 x F2	65.00 ± 0.29 b	10.93 ± 0.07 bc
<i>Significance</i>	*	*

E1 - sowing time I, E2 - sowing time II, NF - non-fertilized control, F1 - fertilized with PromoStart®, F2 - fertilized with Terrenova®; Values are presented as mean ± standard error (SE). Within each column, * - statistically significant difference, values associated to different letters are significantly different according to Tukey's test at $p < 0.05$.

Furthermore, there is a direct physiological correlation between TSS and vitamin C: hexoses (glucose and galactose), which constitute a significant fraction of the soluble solids, act as direct biochemical precursors in the ascorbic acid metabolic pathway (the L-galactose pathway) (Cruz-Rus et al., 2011; Smirnov, 2000). Thus, the high °Brix values observed in the E2 × F1 variant metabolically support the maximum vitamin C concentration (67.33 mg/100 g), indicating an optimal state of physiological activity. The data presented in Table 4 confirm that hemp biomass exhibits high metabolic plasticity. The combination of meteorological conditions characteristic of the E2 sowing epoch and fertilization with F1 favors the accumulation of nutritional compounds, highlighting the potential of mature hemp biomass as a valuable plant source of antioxidants.

Maluleke and Thobejane investigated the combined effects of different types of chemical and organic fertilizers across various growing environments on the yield and biochemical constituents of *Cannabis sativa* for commercial production purposes. The authors reported that vitamin C content ranged from 26 to 66 mg/100 g dry weight (DW), depending on the fertili-

zation type and growing environment (Maluleke and Thobejane, 2025).

Figure 3 presents the influence of sowing time and fertilization treatment on the photosynthetic rate in monoecious hemp. E2 recorded a higher photosynthetic rate than E1, with an improvement of approximately 21.3%. Among fertilization treatments, F1 (PromoStart®) achieved the highest photosynthetic rate ($15.53 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), outperforming both F2 (Terrenova®) and the non-fertilized control.

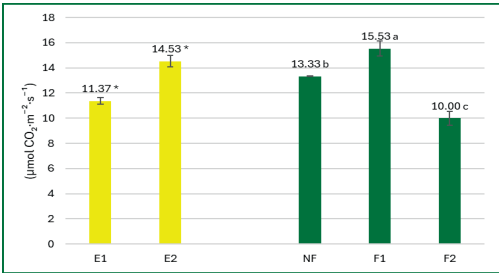


Figure 3. Influence of sowing time and fertilization on the photosynthetic rate

Figure 4 presents the interaction effects between sowing time and fertilization on the photosynthetic rate of monoecious hemp, with statistically significant differences recorded among all six treatment combinations ($p < 0.05$). The E2 $\times$ F1 combination achieved the highest photosynthetic rate ($18.30 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, group a), while the E1 $\times$ F2 combination recorded the lowest value ($9.25 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, group d).

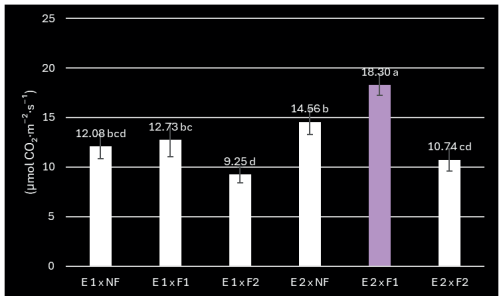


Figure 4. Influence of the interaction between sowing time and fertilization on the photosynthetic rate

Hemp has demonstrated notable photosynthetic capacity, with light-saturated leaf photosynthesis rates recorded at $19 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ under field conditions (Meijer et al., 1995), and more recent studies reporting a

maximum light-saturated net photosynthesis rate (A_{max}) of up to $31.2 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ at 25°C , further highlighting hemp's high resource-use efficiency and bio-economic potential as a crop (Tang et al., 2017).

Figure 5 presents the influence of sowing time and fertilization treatment on soil organic carbon stock (SOCS) in the studied monoecious hemp crop. The soil organic carbon stock (SOCS) values determined at the time of soil sampling were higher in the E2 treatment by approximately 9.4% compared to E1 (68.3 vs. $61.9 \text{ t} \cdot \text{ha}^{-1}$). Regarding fertilization treatments, no statistically significant differences were detected (ns), with the NF variant recording the highest value, exceeding F1 and F2 by approximately 3.7% and 6.5%, respectively.

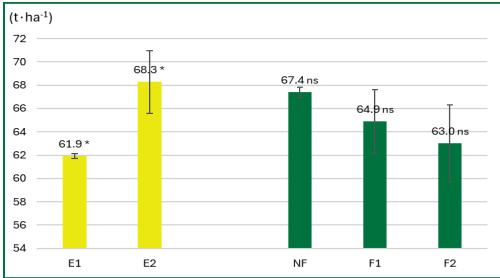


Figure 5. Influence of sowing time and fertilization on soil organic carbon stock (SOCS)

Figure 6 presents the interaction effects between sowing time and fertilization on soil organic carbon stock (SOCS) in the studied monoecious hemp crop, revealing statistically significant differences among treatment combinations ($p < 0.05$).

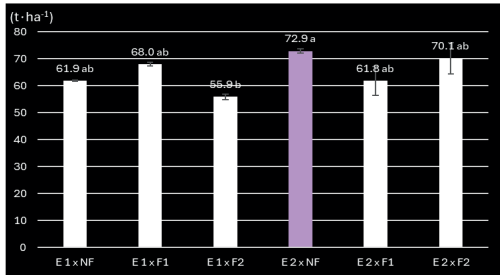


Figure 6. Influence of the interaction between sowing time and fertilization on soil organic carbon stock (SOCS)

The SOCS values determined at the time of soil sampling were highest under the E2 $\times$ NF

treatment (72.9 t·ha⁻¹, group a), exceeding the lowest value observed under E1 × F2 (55.9 t·ha⁻¹, group b) by approximately 23.4%. Furthermore, SOCS values under E2 × NF were higher compared to E2 × F1 and E2 × F2 by approximately 15.2% and 3.8%, respectively. The second sowing date (E2) was associated with higher soil organic carbon stock values, suggesting root - soil interactions and residue dynamics that may favor carbon accumulation in soil under specific phenological conditions. Organic inputs may further modulate soil organic carbon through improvements in soil biological activity and overall soil functioning. Although short-term increases in SOC are promising, longer-term monitoring is necessary to confirm their persistence across seasons and crop rotations.

The PCA results revealed that the first two principal components (PC1 and PC2) accounted for 84.59% of the total variance, with PC1 contributing 49.88% and PC2 34.71%. The third component provided an additional 9.66%, bringing the cumulative explained variance to 94.25%. The remaining components contributed marginally to the total variance, indicating that the first two principal components adequately describe the variability in the dataset (Table 5).

Table 5. Eigenvalues and explained variance of principal components

PC	Eigenvalue	Percentage of Variance (%)	Cumulative Percentage of Variance (%)
1	3.99	49.88	49.88
2	2.78	34.71	84.59
3	0.77	9.66	94.25
4	0.45	5.60	99.85
5	0.01	0.15	100.00

PC1 was positively associated with fresh inflorescence yield (0.447), dry inflorescence yield (0.426), stems yield (0.440), and seed yield (0.439), indicating that this component primarily represents overall productivity traits. PC2 showed strong positive loadings for photosynthetic assimilation rate (0.498), TSS (0.466), and vitamin C (0.465), suggesting that this axis is primarily associated with physiological and quality parameters. The PCA biplot depicted in Figure 7 illustrates the relationships between the interaction of sowing time and fertilization with various hemp characteristics. PC1 distinguishes the experimental variants based on seed yield,

revealing that E1 × F2 and E2 × F2 demonstrate superior performance. In contrast, E2 × F1 is linked to improved photosynthesis, total soluble solids (TSS), and soil carbon content. PC2 emphasizes variations in vitamin C and inflorescence yield, with E1 × F1 showcasing higher yields of inflorescence and stems, alongside moderate levels of vitamin C. The experimental variants without fertilization (E1 × NF and E2 × NF) are positioned at the periphery, indicating lower overall performance.

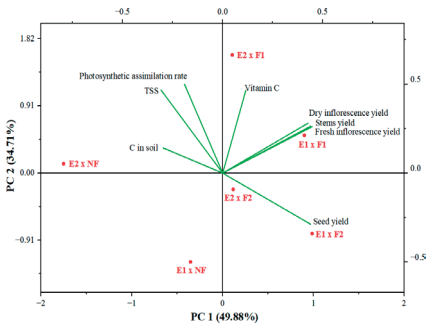


Figure 7. Two-dimensional PCA showing the distribution of analyzed hemp traits as influenced by sowing time and fertilization

The correlation analysis (Figure 8) reinforces the findings from the PCA by elucidating the relationships among various traits. Fresh and dry inflorescence yields, along with stems yield, display a strong positive correlation (0.97–0.99), underscoring that PC1 predominantly reflects overall productivity.

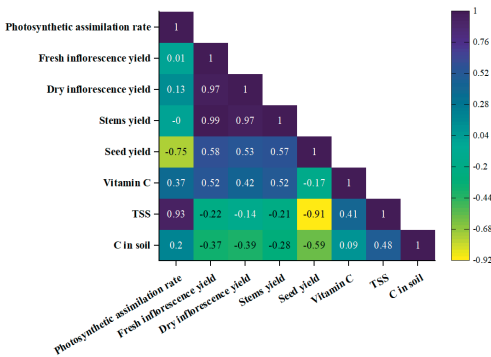


Figure 8. Pearson correlation analysis of hemp traits under the sowing time and fertilization interaction

Seed yield demonstrates a moderate correlation with inflorescence traits (0.53-0.58) but exhibits

strong negative correlations with both the photosynthetic rate (-0.75) and total soluble solids (TSS) (-0.91). This suggests a trade-off between seed production and physiological or quality traits. Similarly, vitamin C is positively correlated with inflorescence yields but negatively correlated with seed yield, aligning with PC2's representation of physiological and quality parameters. Soil carbon content shows moderate correlations with various traits, further emphasizing the distinction between productivity and quality axes in the PCA.

CONCLUSIONS

The results of this study confirm that both sowing time and fertilization treatment significantly influence yield performance, physiological traits, biochemical quality, and soil carbon dynamics in monoecious hemp under temperate continental conditions.

Early sowing proved most effective for maximizing stem and seed yield, as well as inflorescence biomass, by synchronizing crop development with favorable temperature and photoperiod conditions. Later sowing, however, showed advantages in terms of improved photosynthetic efficiency, higher soil organic carbon stock values, and improved biochemical traits.

Among the fertilization treatments, both PromoStart® and Terrenova® consistently outperformed the unfertilized control for the majority of yield and quality parameters. PromoStart® proved most effective in promoting inflorescence and stem biomass, the analyzed biochemical compounds, and photosynthetic rate, while Terrenova®, an organic fertilizer based on humic and fulvic acids, showed particular effectiveness in supporting seed production.

Overall, no single combination of sowing time and fertilization proved universally optimal across all evaluated traits. Future studies should investigate multi-year responses and additional varieties to further optimize agronomic recommendations for this crop.

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