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Research article

Agronomic performance of industrial hemp (*Cannabis sativa* L.) in northern Greece: A comparative study

E. Tsaliki[1,*], T. Tzivara[2], C.A. Damalas[3,*], S. Fotiadis[3], E. Vazanelli[1], I. Panoras[1], T. Moysiadis[1,4] and S.D. Koutroubas[3]

[1] Hellenic Agricultural Organization DIMITRA, Institute of Plant Breeding and Genetic Resources, 57001 Thermi Thessaloniki, Greece
[2] Soufliotika Kelaria, 68133 Alexandroupolis, Greece
[3] Democritus University of Thrace, Department of Agricultural Development, 68200 Orestiada, Greece
[4] Department of Computer Science, School of Sciences and Engineering, University of Nicosia,2417 Nicosia, Cyprus

* **Correspondence:** Email: etsaliki@elgo.gr; chris.damalas@yahoo.gr; Tel: +00302310471544.

Abstract: Industrial hemp (*Cannabis sativa* L.) is a sustainable, high-yielding crop, well adapted to the Mediterranean climate, but little information exists concerning the performance of industrial hemp varieties in the field under common management practices. In this study, we evaluated the agronomic performance of two monoecious industrial hemp varieties, Ferimon and Fedora 17, across two distinct Greek locations (Thermi and Evros) over two consecutive growing seasons (2023 and 2024). The varieties were assessed for key morphological traits, including plant height, stem diameter, internode length, SPAD index, along with biomass production, fiber content, and seed yield. Significant annual variation in industrial hemp growth was noted, with plants in 2023 exhibiting greater plant height (215 vs. 130 cm), stem diameter (9.32 vs. 7.29 mm), internode length (16.9 vs. 10.5 cm), and SPAD readings (49.6 vs. 42.6) compared to 2024. While location had a limited effect on plant height, it significantly influenced other traits, with Evros consistently favoring higher SPAD readings (51.4 vs. 40.7) and longer internodes (14.3 vs. 13.2 cm). Ferimon exhibited superior plant height (178 cm) and seed yield (0.664 t ha^{-1}) across most settings, whereas Fedora 17 demonstrated enhanced fiber content (25.9%) and stem diameter (8.9 mm), especially in Thermi. Industrial hemp plants exhibited Δ9-tetrahydrocannabinol (THC) levels between 0.10% and 0.12%, consistently below the 0.3% EU regulatory threshold, demonstrating successful compliance within Mediterranean cultivation systems. However, the presence of three-way interactions (year x location x variety) for most agronomic parameters highlighted the need for environment-specific cultivar recommendations. The findings provide valuable insights into varietal adaptability of industrial hemp in Greece and contribute to strategic decision-making in industrial hemp cultivation in Mediterranean environments.

Keywords: agronomic performance; genotype x environment interaction; plant height; fiber yield; seed yield

1. Introduction

Cannabis sativa L. belongs to the family Cannabaceae and has been cultivated worldwide for centuries as a sustainable crop, producing many different end-products [1]. Although hemp was first cultivated for fibers and textiles, nowadays, with the recent revival of the crop, all the parts and by-products of the plant are used for pharmaceutical uses, nutrition and functional foods, feed, paper production, biofuels, bio-composites, cosmetics, and construction [2].

Approximately 30 countries across Europe, Asia, North America, and South America legally cultivate hemp. Among them, Canada, China, and the European Union represent the leading global producers [1]. In Europe, in order to meet the standard eligibility conditions for direct payments, farmers have to use certified seed of the varieties listed in the EU common catalogue of varieties, with a Δ9-tetrahydrocannabinol (THC) content below 0.3%, although the national limits may be different [3,4]. Since 2016, Greece has experienced a revival in hemp cultivation, with various cultivars being grown. The success of this cultivation is influenced not only by market demands but also by the legislative framework governing the final product market [5].

Hemp is an annual, wind-pollinated crop, with dioecious and monoecious varieties [6]. The ability to utilize the entire plant for multiple purposes creates opportunities for the market to value hemp products [7]. Crop management practices influence both hemp's yield and the synthesis of key cannabinoids, while the environment and the choice of the proper genotype are crucial for overall performance in the field [8]. Indeed, the agronomic performance of industrial hemp depends on key phenotypic traits, such as plant height, stem diameter, seed yield, and fiber content. These characteristics are strongly influenced by genotype x environment interactions [9]. Cultivation takes place in well-drained and medium–heavy soils, rich in organic matter [9,10]. In addition, optimal conditions for hemp cultivation include average temperatures between 16–27 °C and annual precipitation ranging from 500 to 700 mm [11]. Hemp has a well-developed root system preventing soil erosion and has lower water and fertilizer requirements compared to other crops. Sowing mainly takes place during spring (March-May) in the northern hemisphere, and the time required from sowing to harvesting is 3–4 months, depending on variety [6].

Beyond its traditional uses, hemp has gained attention for its potential in phytoremediation due to its ability to accumulate heavy metals while maintaining robust growth. Researchers have explored its zinc (Zn)-phytoextraction capacity when assisted by biodegradable chelating agents. Specifically, the researchers in [12] reported that nitrilotriacetic acid significantly enhanced Zn uptake in the variety Felina 32, while citric acid showed minimal effects but milder impacts on soil microbiota. These findings highlight the importance of genotype-specific approaches and the need to balance remediation efficiency with soil ecosystem health [12].

Hemp seeds are mainly used as animal feed, but their products (oil, meal, flour, and protein powder) are gaining traction on the market with a growing interest in their usage for human nutrition.

Hemp seeds are used in human nutrition and show a high nutritional value, either as flour or as oil [13]. Hemp seed consists of 20 to 30% edible oil, 20 to 30% protein, 20 to 25% fiber, 20 to 30% carbohydrates, and many other important nutrients and vitamins [14]. Hemp seed oil is characterized by high polyunsaturated fatty acids content and low saturated fatty acids, a unique ω6 to ω3 ratio, high tocopherol, phytosterol, and phenolic content that elevates its nutritional value [15]. Hemp seeds have also been demonstrated to improve the quality of animal-derived foods. For instance, dietary supplementation with hempseed expellers in broiler chickens has been found to enhance meat color and odor, suggesting potential added value for both animal health and consumer appeal [16].

Considering that there is growing interest in worldwide hemp cultivation due the multitude of end products, its cultivation is expected to rise notably over the next years [11]. Despite the favorable weather conditions for hemp growth in southern Europe, there is little background knowledge regarding the adaptability and productivity of the registered varieties [17] due to the interruption of hemp production in the second half of the last century. However, there is significant interest among farmers in reintroducing hemp cultivation. Therefore, the primary objective of this research was to evaluate the characteristics of hemp cultivars in specific Greek environments, providing farmers with valuable data to aid in selecting the most suitable varieties for their intended end products.

2. Materials and methods

During the years 2023 and 2024, two monoecious varieties, Fedora 17 and Ferimon of French origin, were cultivated in Evros region of Thraki, Greece and in Thermi region of Central Macedonia, Greece. The varieties were chosen because they are fast growing and well-adapted to the Mediterranean environment, with a small to medium biological cycle. Both varieties can be used for grain or fiber production and obtained from Hempoint [18], according to the requirements of the Greek legislation.

The experimental fields were established at the campus of Institute of Plant Breeding and Genetic Resources (IPBGR) in Thermi (Thessaloniki). In particular, in 2023, the trials were established at field A, at 40.536440 N and 23.006912 E, while in 2024, the trials were established at a nearby field B, at 40.536416 N and 23.001569 E, for crop rotation issues. In Evros, the experiments were established in Ferres, in the same field (40.82290 N, 26.17280 E) both years. Soil properties were determined at the Soil Science Institute of ELGO-DIMITRA, following [19] and are presented in Table 1.

Table 1. Major soil properties of experimental fields in Thermi and Evros.

Property	Thermi		Evros	
	2023	2024	2023	2024
Sand (%)	52	42	60	52
Silt (%)	34	36	20	28
Clay (%)	14	22	20	20
pH	7.9	7.7	7.8	7.01
Organic matter (%)	1.2	2.2	0.96	1.13
EC (mS/cm)	0.45	0.47	0.54	0.91
NO_3-N (ppm)	7.1	7.8	12.8	18.93
P (ppm)	3.6	9.1	24.58	28.84
K (ppm)	138	337	182	276

The climate in the experimental areas is characterized as typically Mediterranean, with a warm, dry summer and a cool, humid winter. The mean monthly temperatures and the total monthly rainfall data, which were recorded near the experimental area (over a distance of approximately 1000 m), are shown in Figure 1.

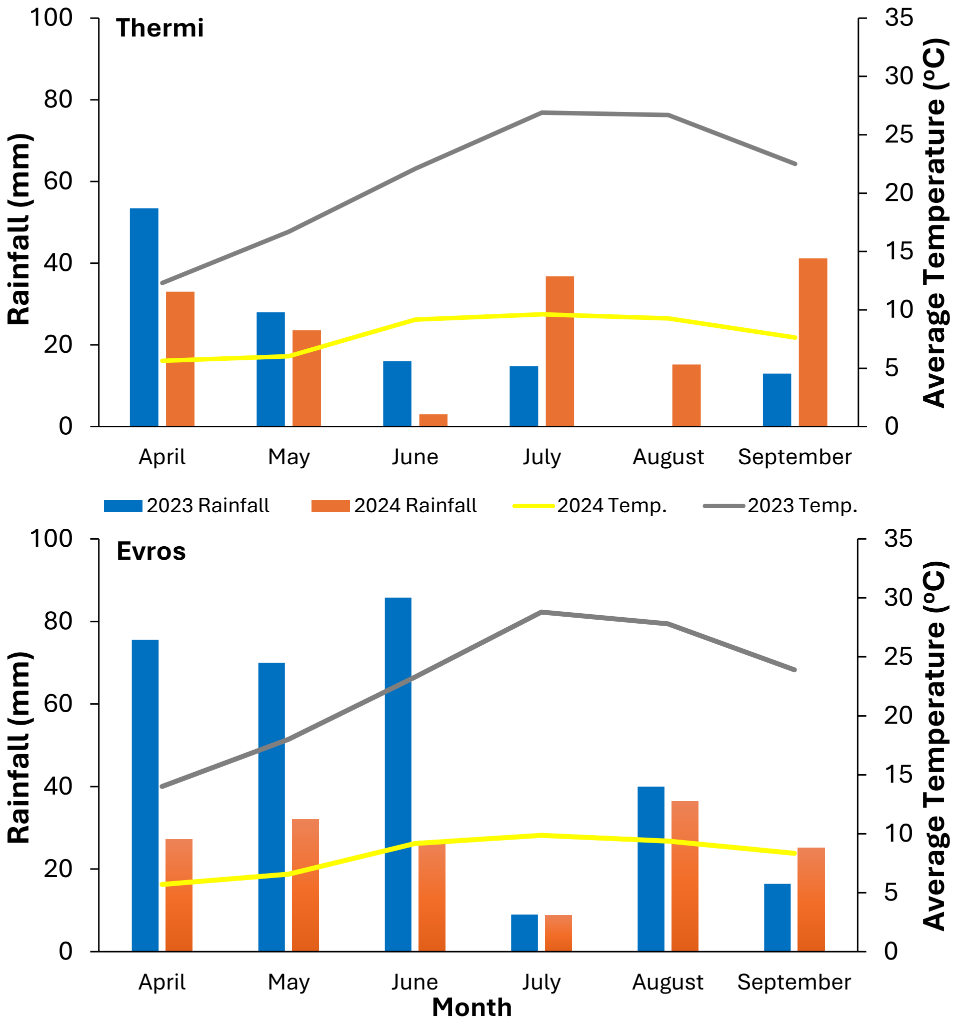

Figure 1. Monthly rainfall and average temperatures from April to September in 2023 and 2024 for the experimental sites in Thermi and Evros (data source: https://www.meteo.gr/).

In Evros, hemp was machine-seeded using a pneumatic machine (Gasparo) on 21 May 2023 and 14 May 2024, with a seeding rate of 20 kg ha^{-1} at a row distance 80 cm. In Thermi (Thessaloniki), hand-sowing took place on 25 April 2023 and 17 April 2024 in plots of 5 m length with 80 cm distance between rows and 10 plants per meter. Each plot consisted of 4 hemp rows. Plots were arranged in a randomized complete block design, with three replications. The previous crop in all fields was durum wheat.

In all experimental fields, the seedbed was prepared with a moldboard plough followed by disc-harrowing. One day before sowing, basic fertilization was applied, including nitrogen in the form of ammonium sulfate [$(NH_4)_2SO_4$], phosphorus in the form of triple superphosphate [$Ca(H_2PO_4)_2$], and potassium in the form of potassium sulfate (K_2SO_4) with common 20.5-0-0, 0-46-0, and 0-0-50 fertilizers, respectively, as described in Table 2. Topdressing nitrogen as ammonium nitrate (NH_4NO_3)

fertilization of the 33.5-0-0 fertilizer was applied at the beginning of anthesis each year, only in Thermi (Thessaloniki) (Table 2).

Table 2. Fertilization rate in the experimental fields.

		Fertilization rate (kg ha^{-1})			
		Basic			N-topdressing
Year	Sowing date	20.5-0-0	0-46-0	0-0-50	33.5-0-0
2023	25 April/Thermi	400	330	500	200
	21 May/Evros	180	50	184	0
2024	17 April/Thermi	500	260	360	200
	14 May/Evros	180	50	180	0

The experimental area received irrigation applied with sprinklers until crop emergence, whereas drip irrigation was applied thereafter, whenever needed. No pesticides were applied during the growing seasons.

In all fields, several agronomical traits of both varieties were evaluated 65 days after planting (DAP) at the growing stage code 2305 (beginning of seed maturity) [20], according to UPOV protocol [21] for 20 marked plants in each plot. Specifically, the height (cm) of the main stem, the internode length (cm), the stem diameter (mm), and the content of chlorophyll with SPAD (Soil Plant Analysis Development) indicator (SPAD 502DL Minolta, Japan) were measured. Stem diameter and internode length were measured below on the last opposite, fully expanded leaves [21]. THC content was determined in composite samples (one pooled sample per variety per year) to verify regulatory compliance with the THC threshold of EU (0.3%). The THC analysis was performed using a TRACE™ Gas Chromatograph (Thermo Scientific, Fitchburg, WI, USA), equipped with an AS3000 autosampler and a Flame Ionisation Detector (FID), according to the official EU method [4], as described in [17].

In Evros, the fields were machine-harvested (Figure 2) when 70% of the plants reached maturity. Plants were air dried in the dark, threshed and cold-pressed for oil-seed production.

Figure 2. Hemp harvesting (left) and hempseed production (right) in Evros area.

In Thermi, the hemp plants that grew within 1 m of each plot's central rows were hand-harvested at the growing stage code 2305 (beginning of seed maturity) [20]. A digital scale (DELMAC Instruments, EU) was used to determine the total fresh biomass. As reported in [17], the stems were removed from the inflorescences manually, and following wet retting, the percentage of fibers was determined. The hemp plants growing in the other central row of each plot, which was 1 m in length, were also cut at seed harvest 120–130 DAP, at growing stage code 2307 (end of seed maturity) [20] and allowed to dry naturally outdoors. Following drying, shivering and an aspirator (model Selecta Zig Zag, PETKUS Selecta, etc.) were used to separate the seeds from the leaves and stems. The 1000-seeds weight was evaluated with the laboratory counter (MEZOS spot s.r.o., Hradec Králové, Czech Republic) three times per sample.

Data were evaluated using analysis of variance (ANOVA) with the MSTAT-C statistical software (version 1.41, Michigan State University, East Lansing, MI, USA). Prior to conducting the combined analysis, the homogeneity of variances was assessed using Bartlett's test. Treatment means were compared using the Least Significant Difference (LSD) test.

3. Results and discussion

The ANOVA results and means of agronomical traits for the two hemp varieties (Ferimon and Fedora 17), including plant height, stem diameter, internode length, and SPAD values across two years (2023 and 2024) and two locations (Thermi and Evros), are presented in Tables 3 and 4, respectively.

Table 3. Results of analysis of variance (mean squares) for the agronomical traits of Ferimon and Fedora 17 hemp varieties tested in Thermi and Evros areas in 2023 and 2024.

Source of variation	df	Plant height	Stem diameter	Internode length	SPAD
Year (Y)	1	57871.42**	33.05**	325.57**	389.55**
Location (L)	1	72.24ns	95.63**	10.29*	920.10**
Y x L	1	814.26*	0.10ns	162.22**	194.59**
Variety (V)	1	1100.04**	11.57**	135.10**	536.53**
Y x V	1	2480.90**	8.26**	23.62**	230.32**
L x V	1	4274.43**	0.67ns	31.62**	14.27ns
Y x L x V	1	81.70ns	54.18**	0.002ns	45.58ns

*, ** Significant at P = 0.05 and P = 0.01, respectively; ns = not significant.

The agronomic performance of the two hemp varieties was strongly influenced by the year of experimentation. In 2023, the overall mean plant height (215.04 cm) was approximately 65% higher than that in 2024 (129.99 cm). In most cases, Ferimon exhibited greater plant height than Fedora 17, except in Thermi during 2023, where Fedora 17 was taller. This substantial interannual variation reflected a genotype x environment interaction, consistent with the findings of Tang et al. (2016). In addition, the results underscored the sensitivity of hemp growth to climatic variability, agreeing with findings from Northern Italy [22]. Nevertheless, plant architecture, including height and branching patterns, can be modulated through the exogenous application of plant growth regulators, such as 1-naphthylacetic acid and 6-benzylaminopurine [23].

Stem diameter varied significantly across years and locations, without a consistent trend between the two varieties. In 2023, Fedora 17 exhibited a markedly higher stem diameter than Ferimon in Evros, whereas in 2024, the opposite was observed. Similarly, in Thermi, Ferimon had a slightly higher stem diameter in 2023, but Fedora 17 outperformed in 2024. Comparable results were reported by [11], who observed improved stem thickness under favorable environmental and fertilization regimes in Central Italy.

Table 4. Agronomic traits of Ferimon and Fedora 17 hemp varieties in Thermi and Evros areas in 2023 and 2024.

Year	Location	Variety	Plant height (cm)	Stem diameter (mm)	Internode length (cm)	SPAD
2023	Thermi	Ferimon	198.60 b	11.15 a	12.17 c	39.80 cd
		Fedora 17	224.40 a	11.06 a	16.02b	43.68 bc
		Mean	211.50 A	11.10 A	14.10 B	41.74 C
	Evros	Ferimon	225.60 a	5.27 d	15.83 b	56.51 a
		Fedora 17	211.57 ab	9.80 b	23.63 a	58.28 a
		Mean	218.58 A	7.53 A	19.73 A	57.40 A
	Mean		215.04 A	9.32 A	16.91 A	49.57 A
2024	Thermi	Ferimon	138.05 cd	7.42 c	12.03 c	34.78 e
		Fedora 17	135.03 d	10.50 ab	12.41 c	44.61 b
		Mean	136.54 B	8.96 A	12.22 C	39.70 C
	Evros	Ferimon	151.27 c	6.97 c	6.65 d	36.85 de
		Fedora 17	95.62 e	4.26 d	11.05 c	54.13 a
		Mean	123.44 C	5.61 A	8.85 D	45.49 B
	Mean		129.99 B	7.29 B	10.53 B	42.59 B

Means in a column followed by the same lowercase letter are not significantly different at P = 0.05. Location or yearly means in each column followed by the same uppercase letter are not significantly different at P = 0.05.

Internode length varied significantly with year and location. Overall, internode length was 61% higher in 2023 (16.91 cm) than in 2024 (10.53 cm). In 2023, varietal differences were evident in both locations, while in 2024, differences were significant only in Evros. The SPAD index, an indication of leaf chlorophyll concentration and plant health, was higher in Evros than in Thermi across both years. Regarding the year of experimentation, the overall mean SPAD values were 16% higher in 2023 (49.57) compared to those in 2024 (42.59), aligning with overall better plant performance in 2023. These observations agree with [24], who associated favorable environmental conditions with greater internode elongation in monoecious hemp.

Overall, the year had a greater influence on all agronomic traits compared to location. However, significant interactions between year x variety and location x variety were observed, indicating that plant responses depend on the growing season and location-specific conditions. Hemp performance is more susceptible to intra-field variability and interannual climate fluctuation than to cultivar influences [25]. This emphasizes the necessity of tailoring variety selection and management practices to specific environments and years. Tang [26] also found significant effects of genotype on stem yield, plant height, and stem diameter in all four European locations of their experimentation.

Table 5 presents the ANOVA results and Table 6 provides the mean values of biomass production (fresh and dry), fiber percentage, seed yield, and the 1000-seeds weight for both hemp varieties (Ferimon and Fedora 17) in Thermi. Statistically significant differences were observed between the two years for most traits. In 2023, plants exhibited higher fresh biomass (29.325 t ha^{-1}), dry biomass (9.262 t ha^{-1}), seed yield (0.833 t ha^{-1}), and 1000-seeds weight (13.483 g), compared to 2024. The fiber percentage, however, was significantly higher in 2024 (25.45%) than in 2023 (21.73%), suggesting that while overall biomass and seed production decreased in 2024, the relative allocation to fiber content increased. ANOVA results support these observations, showing significant year effects on all traits ($p < 0.05$ or $p < 0.01$), with the strongest effects on seed yield and 1000-seeds weight.

Table 5. Results of analysis of variance (mean squares) for harvesting traits of Fedora17 and Ferimon varieties in Thermi, for the years 2023 and 2024.

Source of variation	df	Fresh biomass	Dry biomass	Fibers	Seed yield	1000-seeds weight
Year (Y)	1	280.56*	29.32*	55.28*	782782.6**	45.77**
Variety (V)	1	28.09ns	6.68ns	86.96**	42952.6ns	17.35**
Y x V	1	47.61ns	8.04ns	18.06ns	430.6ns	0.001ns

*, ** Significant at P = 0.05 and P = 0.01, respectively; ns = not significant.

Table 6. Harvesting traits of Fedora17 and Ferimon hemp varieties tested in Thermi for 2023 and 2024.

		Fresh biomass (t ha^{-1})	Dry biomass (t ha^{-1})	Fibers (%)	Seed yield (t ha^{-1})	1000-seeds weight (g)
Year	2023	29.325 a	9.262 a	21.73 b	0.833 a	13.483 a
	2024	20.950 b	6.555 b	25.45 a	0.391 b	10.100 b
Variety	Ferimon	26.463 a	8.555 a	21.26 b	0.664 a	12.832 a
	Fedora 17	26.813 a	7.263 a	25.92 a	0.560 a	10.750 b

Means in a column followed by the same lowercase letter are not significantly different at P = 0.05.

Comparing the two varieties, no statistically significant differences were observed in fresh or dry biomass production. This finding showed that both hemp varieties, Ferimon and Fedora 17, exhibited comparable productivity in terms of biomass under the specific environmental and management conditions of this study. These findings are consistent with results from previous research conducted in Latvia, where Ferimon and Fedora 17 showed similar dry biomass yields [27]. Fedora 17 exhibited a higher fiber percentage (25.92%) than Ferimon (21.26%), suggesting its potential suitability for fiber-oriented cultivation. In contrast, Ferimon exhibited a heavier 1000-seeds weight (12.832 g) than Fedora 17 (10.750 g), indicating an advantage in seed size. These findings are in line with previous research emphasizing genetic variability in seed and fiber traits among monoecious hemp cultivars. Although Fedora 17 is often proposed as a variety well-suited for seed production, the reported yields can vary greatly depending on environmental conditions and cultivation practices [22,26].

The hemp plants in Thermi were hand harvested and the seed yield reached a maximum in 2023 (Table 6), while in Evros, machine harvesting resulted in lower yields ranging between 0.300 and 0.400 t ha^{-1}. According to the seed distributors [18], the seed yield for Ferimon is 0.8-1.0 t ha^{-1}, while for Fedora it is greater than 1.2 t ha^{-1}. The low yields in Evros were mainly because of mechanical harvesting, which is not properly developed in hemp cultivation, and seed loss due to natural dehiscence or machinery inefficiencies makes the process particularly challenging. Furthermore, the harvesting process is complicated by the height of the plants, their strong and highly lignified fibers, and birds feeding in the fields [28], along with the huge amount of fresh biomass to be handled by the harvesting machines.

In Greece, data from experiments in the 2016–2023 period demonstrated that the fresh biomass yield for Ferimon was 33.9 t ha^{-1}, while for the Fedora 17 variety, it reached 36.25 t ha^{-1} [29]. Moreover, hemp exhibits indeterminate growth, with seed maturation beginning at the bottom of the seed head and progressing upward. This pattern leads to a situation where mature seeds are found lower down, while immature green seeds remain at the top. Additionally, when seeds reach maturity, the bracts that enclose them dry out, making the seeds more susceptible to shattering and, consequently, leading to significant seed loss [30]. Furthermore, birds can pose a threat to seed-producing crops, as their feeding on maturing hemp seeds may further contribute to shattering and yield loss [31], which is an important factor to consider when planning the harvest timing of hemp.

Table 7. Δ9-tetrahydrocannabinol (THC) content (% w/w) of Fedora 17 and Ferimon hemp varieties grown in Thermi during 2023 and 2024.

Year	Variety	THC content (%)	Compliance with EU regulation (<0.3%)
2023	Ferimon	0.12	Yes
	Fedora 17	0.11	Yes
2024	Ferimon	0.10	Yes
	Fedora 17	0.12	Yes

The THC content of all composite samples ranged narrowly between 0.10% and 0.12% (Table 7), well below the EU regulatory threshold of 0.3% for industrial hemp cultivation [5]. Although the composite sampling protocol (one pooled sample per variety/year) did not permit statistical comparisons between treatments, the consistent compliance of all samples confirms the feasibility of cultivating industrial hemp in Mediterranean environments, also adhering to EU regulatory standards. In addition, the findings suggest stable varietal performance in terms of THC content under the tested agronomic conditions.

Overall, industrial hemp has potential to become a promising crop for producing value-added products in Greece. Optimal performance of hemp depends on the interaction between climatic conditions and agronomic practices. Selecting appropriate row spacing and nutrient sources is essential for enhancing hemp production while reducing input costs and minimizing environmental impact [32].

4. Conclusions

In this research, we evaluated certain agronomic characteristics of two industrial hemp cultivars in specific Greek environments, providing farmers with valuable data for selecting the most suitable varieties for their intended end products. There were significant differences between the two varieties regarding plant height over years, but not between locations. The year also had a significant effect on stem diameter, internode length, and SPAD values. In general, both varieties showed adaptability and acceptable agronomic characteristics for biomass and seed production at the experimentation locations in Greece, providing useful information to farmers for choosing the most appropriate variety according to the end use and to use the most efficient production techniques and procedures. Nevertheless, additional research should be conducted for different genotypes to find agronomical practices that can improve alternative hemp yields, such as the production of inflorescences for medicinal use and seeds for oil and flour, grown under Mediterranean conditions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflicts of Interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, E.T., T.T. and S.D.K.; investigation, E.V., I.P. T.M., C.A.D and S.F.; writing—original draft preparation, E.T., S.D.K.; writing—review and editing, E.T. and S.D.K.; supervision, E.T., T.T. and S.K. All authors have read and agreed to the published version of the manuscript.

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