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ELEMENTS OF PRODUCTIVITY AND FIBER QUALITY IN INDUSTRIAL HEMP, *Cannabis sativa* L.

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Abstract

*The study analyzed three genotypes of industrial hemp, Cannabis sativa L., under the aspect of fiber productivity indices in relation to plant parameters. The study took place in ARDS Lovrin, Romania. The genotypes Silvana (control), Teodora and Lv-300 were evaluated. The experiment took place under the conditions of a chernozem type soil, non-irrigated system. Several parameters and indexes were analyzed: total plant weight (TPW), stem length (SL), inflorescence length (IL), technical length (TL), middle stem diameter (MSD), dry sample weight (DSW), dry fiber content (DFC), pure fiber weight (PFW), and technical fiber (TF). The DFC index showed positive correlations with SL (r=0.708***), with MSD (r=0.712***), with DSW (r=0.739***), with TPW (r=0.546**), and with TL (r=0.399*). The PFW index showed negative correlations with TPW (r=-0.493**) and with DSW (r=-0.373*). Technical fiber (TF) showed very strong, positive correlations with PFW (r=0.999***) and negative correlations with other parameters (e.g. with TPW, r=-0.493**, with DSW, r=-0.373*). From the comparative analysis of Teodora in relation to Silvana, average values TF_T=31.355 (Teodora) and TF_S=28.388 (Silvana) resulted, and the differences showed statistical certainty (t=2.5948, with p=0.013; U=72, p=0.0045; p<0.05). From the comparative analysis of Lv-300 in relation to Silvana (control), mean values TF_T=29.357 (Lv-300) and TF_S=28.388 (Silvana) resulted, but the differences did not show statistical certainty (t=0.763, with p=0.451; U=117, p=0.158; p>0.05). The regression analysis led to equations and graphic models that described the variation of fiber productivity indices in relation to plant biometric parameters.*

Key words: *biometric parameters, industrial hemp, multifunctional crop, productivity indices, technical fiber*

INTRODUCTION

Industrial hemp (*Cannabis sativa* L.) is an annual herbaceous plant, native to the temperate regions of Central Asia [7]. Industrial hemp (*Cannabis sativa* L., Cannabaceae) is a crop plant with a long history as a cultivated plant, valued since ancient times for its fibers, as a food resource and medicinal uses, with a complex functional role in all types of agricultural systems of over time, and even more so for the future [15, 16].

As a result of the similarities and some associations between industrial hemp (fibers, seeds) and the narcotic (medicinal) type of cannabis, the cultivation and production of industrial hemp was prohibited in most countries for quite a long period of time, which led to the loss of knowledge accumulated over centuries of learning, as well as to the loss of some valuable genetic resources [16]. The current position, adopted about two decades ago, makes most countries legalize the production of industrial hemp, and industrial hemp is seen as a multifunctional plant for the global food chain [16].

Industrial hemp is a plant that is based on the concept of "circular economy", in that it has multiple functionalities: ecological crop, friendly to the environment; contributes to CO_2 fixation; contributes to soil protection; provides resources for different industries – textile products, food, construction, furniture, pulp and paper, cosmetics, composite materials, biofuels, bioplastics, biopesticides, etc.) [15].

Hemp is increasingly used in food, as food, functional foods, or food ingredients. For food safety and consumer health, related to THC, it is necessary to comply with the regulations in force (<0.3% Tetrahydrocannabinol – THC), when using hemp in food for the safety of the food product [1].

As a result of the high economic profitability potential of industrial hemp in established countries (for seeds and fibers), there is interest in expanding the cultivation of industrial hemp in new areas with tropical climate conditions.

Recent studies have used simulation models to simulate and map the yield potential of hemp in relation to climatic conditions and to map the areas with minimum feasible productions (fibers, seeds) in order to expand the cultivation of hemp in new areas, such as some tropical countries, e.g. Malaysia and other Asian countries with tropical conditions [17].

As a result of the importance of industrial hemp, various studies have evaluated the opportunity of building and developing an industry based on industrial hemp, from a food perspective (seeds, flour, protein, hemp seed oil). As a result, the directions of agronomic approach, farm management, product valorisation (farm, and post-farm strategies), but also improvement programs and selection of valuable genotypes were outlined, all associated with opportunities led by the market [3].

Due to the directions of alternative use of hemp, which are of increasing interest compared to traditional use, recent studies have concatenated classical knowledge regarding industrial hemp with current knowledge, in order to outline new research paths, and advanced applications of industrial hemp [13].

Under the conditions of the "Farm Bill" standards, in the USA, in the State of Arkansas, it was found, based on restricted linear programming models, the increase of the area cultivated with industrial hemp by 2.8 - 4.4% and the increase of profit at the state level by 0.3 - 18.2% [14]. The results communicated based on the study [14], confirmed the profitability of the industrial hemp crop, and support the consideration of this crop in the conditions of the sustainable economy. In the state of Florida (USA), after the Legislative Session of 2019, there were various scientific analyzes and presentations in the media, in order to inform about policies and the economic potential for the production of industrial hemp [12].

Starting from compliance with "Farm Bill 2018" (<0.3% THC) Barnes et al. (2023) [2] studied the possibility and profitability of cultivating industrial hemp (fiber production) interspersed with a plantation of loblolly pine (*Pinus taeda*). Based on the simulation of some information and data, and some growth models, the authors of the study recorded that the interspersed culture of pine and hemp, under the conditions of the study, can generate higher profits by about 25% compared to the pure culture (monoculture) of pine loblolly. The results communicated by the authors show high interest for agricultural and agro-forestry systems, in order to increase productivity and economic benefits.

Recent studies carried out in the USA [11] have highlighted the importance of industrial hemp and its potential as a sustainable crop in the context of climate change, by the fact that it meets the conditions of the "pillar of sustainability" (the "economy-environment-society" triangle).

At the EU level, from statistical data [5], it was found that the area cultivated with industrial hemp has increased, from 20,540 ha (year 2015) to 33,020 ha (year 2022), which represents an increase of approx. 60%.

Hemp production registered an increase from 97,130 t to 179,020 t, in the same period 2015 - 2022, which represents an increase of about 84.3%. Within the EU countries, France occupies the first place (> 60% of the EU production), followed by Germany (approx. 17% of the EU production) and the Netherlands (approx. 5% of the EU production).

The present study evaluated elements of productivity and quality of the fiber in relation to physiological indices and biometric parameters of the plants in three industrial hemp genotypes, *Cannabis sativa* L. in order to describe through mathematical and graphical models the variation of the elements of fiber productivity, with importance in breeding programs for industrial hemp and for crop technologies.

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MATERIALS AND METHODS

The study evaluated fiber productivity elements in relation to biometric parameters and plant physiological indices in industrial hemp, *Cannabis sativa* L. The study took place in the experimental conditions of ARDS Lovrin, Romania. Three varieties of industrial hemp were analyzed, Silvana (as control), Teodora, and Lv-300. The experiment took place under the conditions of a chernozem type soil, non-irrigated system, period 2021 - 2022. The general aspect of the comparative crop of industrial hemp, which included the three analyzed varieties, is presented in Photo 1. The climatic conditions, in terms of the pluviometric and thermal regime during the study period, are presented in Fig. 1.

Photo. 1. Experimental field, industrial hemp (*Cannabis sativa* L.), ARDS Lovrin
Source: Original photo taken by the authors.

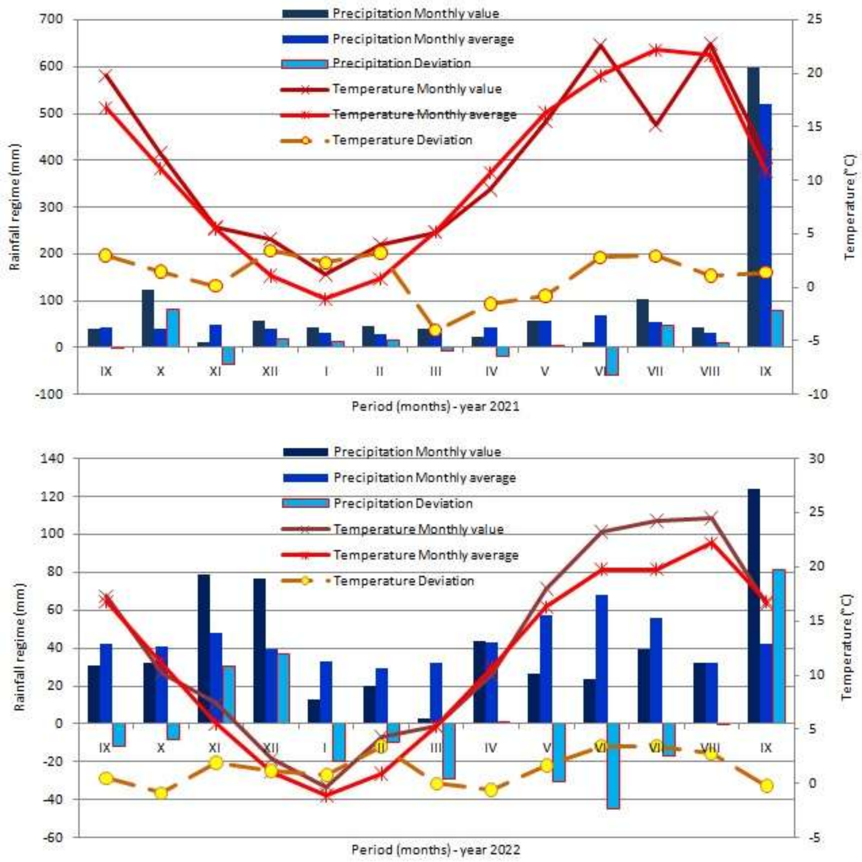


Fig. 1. Climatic conditions during the study period, ARDS Lovrin
Source: Original figure, generated by the authors

The experimental variants were cultivated in three repetitions. In order to determine the biometric parameters and productivity elements, according to the study protocol, elite plants were extracted from each variant and repetition. Within the biometric and physiological parameters of the elite plants and the elements of fiber productivity were determined: total plant weight (TPW), stem length (SL), inflorescence length (IL), technical length (TL), middle stem diameter (MSD), dry sample weight (DSW), dry fiber content (DFC), pure fiber weight (PFW), and technical fiber (TF).

The recorded results were analyzed for a general statistical description. The Anova test was applied for specific statistical evaluation (Alpha=0.001). The correlation analysis was used to identify the interdependence between the parameters and indices of the elite plants, considered in the study. The regression analysis was applied to find equations and models describing the variation of some fiber indices in relation to biometric parameters. The comparative analysis between the studied genotypes, Teodora, Lv-300 and Silvana (considered as control) was made with regard to technical fiber (TF), as a representative fiber productivity index (t-test, Mann-Whitney non-parametric test). In relation to the purpose of the study, appropriate mathematical and statistical analysis tools were used [8, 9, 18].

RESULTS AND DISCUSSIONS

From the analysis of the elite plants of the three varieties of industrial hemp (Silvana, Teodora, Lv-300) the values of the biometric and fiber parameters were obtained. The descriptive statistical analysis led to the data in Table 1. The total weight of the elite plants (TPW) varied between 78.00 – 226.00±8.866 g. The stem length of the elite plants (SL) varied between 221.00 – 311.00±6.442 cm, and the technical length (TL) varied between 120.00 – 227.00±6.557 cm. The diameter at the middle of the elite plants (MSD) varied between 9.12 – 14.79±0.335 mm. The dry weight of the samples (DSW) varied between 17.55 – 46.72±1.812 g. Dry fiber content (DFC) varied between 4.29 – 8.11±0.288 g. Pure fiber weight (PFW) varied between 17.18 – 27.18±0.672 %. Technical fiber (TF) varied between 22.34 – 35.33± 0.874 %. The Anova test confirmed the statistical reliability of the data and the presence of variance, Table 2.

Table 1. Descriptive statistics

Statistical parameters	TPW	SL	IL	TL	MSD	ST/TL	DSW	DFC	PFW	TF
Valid	18	18	18	18	18	18	18	18	18	18
Missing	0	0	0	0	0	0	0	0	0	0
Median	110.50	252.50	93.00	157.50	11.91	1.58	25.25	6.08	22.71	29.52
Mean	120.00	257.61	93.50	164.11	11.68	1.59	26.87	6.00	22.85	29.70
Std. Error of Mean	8.866	6.442	3.912	6.557	0.335	0.042	1.812	0.288	0.672	0.874
Std. Deviation	37.614	27.333	16.596	27.819	1.42	0.176	7.69	1.223	2.853	3.708
Minimum	78.00	221.00	73.00	120.00	9.12	1.32	17.55	4.29	17.18	22.34
Maximum	226.00	311.00	135.00	227.00	14.79	2.13	46.72	8.11	27.18	35.33
25th percentile	94.50	234.25	81.00	147.25	10.69	1.48	20.63	4.96	21.08	27.41
50th percentile	110.50	252.50	93.00	157.50	11.91	1.58	25.25	6.08	22.71	29.52
75th percentile	141.50	278.75	104.75	174.75	12.60	1.64	30.46	6.82	24.87	32.33

Source: Original data resulting from the calculation.

Table 2. Anova test

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1155365	9	128373.8	274.8338	2.14E-96	3.293745
Within Groups	79406.37	170	467.0963			
Total	1234771	179				

Source: Original data resulting from the calculation.

Correlation analysis (Kendall's Tau B) led to the values in Table 3. Correlations were recorded between the biometric parameters of the elite plants and the analyzed productivity indices, under statistical safety conditions. For the DFC index, positive, moderate correlations were recorded with SL (r=0.708***), with MSD (r=0.712***) and with DSW (r=0.739***), and weak correlations with TPW (r =0.546**), and with TL (r=0.399*). For the PFW index, negative correlations of weak intensity were recorded with TPW (r=-0.493**) and with DSW (r=-0.373*). Technical fiber (TF) is the index of high importance in the assessment of fiber production and valuable genotypes, and in the case of this index, very strong, positive correlations were recorded with PFW (r=0.999***) and negative correlations with the other parameters, and with statistical assurance in the case of TPW (r=-0.493**) and with DSW (r=-0.373*). Other correlations were also recorded between the parameters analyzed in the elite plants, some of which were correlated with statistical assurance.

Table 3. Correlation matrix table, Kendall's Tau B

Variable	Correlation parameters	TPW	SL	IL	TL	MSD	ST/TL	DSW	DFC	PFW	TF
TPW	Kendall's Tau B	—									
	p-value	—									
SL	Kendall's Tau B	0.594***	—								
	p-value	< .001	—								
IL	Kendall's Tau B	0.332	0.192	—							
	p-value	0.057	0.27	—							
TL	Kendall's Tau B	0.270	0.616***	-0.198	—						
	p-value	0.12	< .001	0.255	—						
MSD	Kendall's Tau B	0.678***	0.603***	0.317	0.320	—					
	p-value	< .001	< .001	0.068	0.068	—					
ST/TL	Kendall's Tau B	0.060	-0.185	0.638***	-0.572***	0.007	—				
	p-value	0.732	0.288	< .001	< .001	0.97	—				
DSW	Kendall's Tau B	0.704***	0.630***	0.343*	0.320	0.765***	0.007	—			
	p-value	< .001	< .001	0.048	0.068	< .001	0.97	—			
DFC	Kendall's Tau B	0.546**	0.708***	0.277	0.399*	0.712***	-0.020	0.739***	—		
	p-value	0.002	< .001	0.111	0.021	< .001	0.909	< .001	—		
PFW	Kendall's Tau B	-0.493**	-0.157	-0.224	-0.007	-0.320	-0.112	-0.373*	-0.111	—	
	p-value	0.004	0.363	0.197	1.000	0.068	0.519	0.032	0.550	—	
TF	Kendall's Tau B	-0.493**	-0.157	-0.224	-0.007	-0.320	-0.112	-0.373*	-0.111	0.999***	—
	p-value	0.004	0.363	0.197	1.000	0.068	0.519	0.032	0.550	< .001	—
* p < .05, ** p < .01, *** p < .001											

Source: Original data resulting from the calculation.

The variation of the productivity indices was analyzed in relation to the biometric parameters of the plants. The DFC variation depending on the biometric parameters of the elite plants was described by equation (1), under conditions of R^2=0.826, F=15.4676, p<0.001, RMSEP=0.49516.

$$DFC = -4.42002 + 0.00102 \cdot TPW + 0.02188 \cdot SL - 0.00072 \cdot TL + 0.4086 \cdot MSD \quad (1)$$

The PFW variation depending on the biometric parameters of the elite plants was described by equation (2), under conditions of R^2=0.611, F=5.1370, p=0.010, RMSEP= 1.72566.

$$PFW = 17.7130 - 0.0886 \cdot TPW + 0.04726 \cdot SL - 0.00385 \cdot TL + 0.36216 \cdot MSD \quad (2)$$

The TF variation depending on the biometric parameters of the elite plants was described by equation (3), under conditions of R^2=0.613, F=5.13885, p=0.010, RMSEP= 2.24290.

$$TF = 23.0305 - 0.11527 \cdot TPW + 0.06142 \cdot SL - 0.00499 \cdot TL + 0.47066 \cdot MSD \quad (3)$$

As the technical fiber (TF) represents the most expressive productivity index, the variation of this index was analyzed in relation to the biometric parameters of the plants, as a direct influence and interaction. The multiple regression analysis led to obtaining a general equation, equation (4). The values of the coefficients of this equation, and the values of the statistical parameters are presented in Table 4. From the analysis of the data presented in table 4, statistical safety ($p<0.05$) was recorded in the case of three combinations of parameters, respectively TPW with MSD, TL with DSW, and MSD with DSW respectively. For these cases, the 3D graphic models and in isoquants format is presented in Figures 2, 3 and 4.

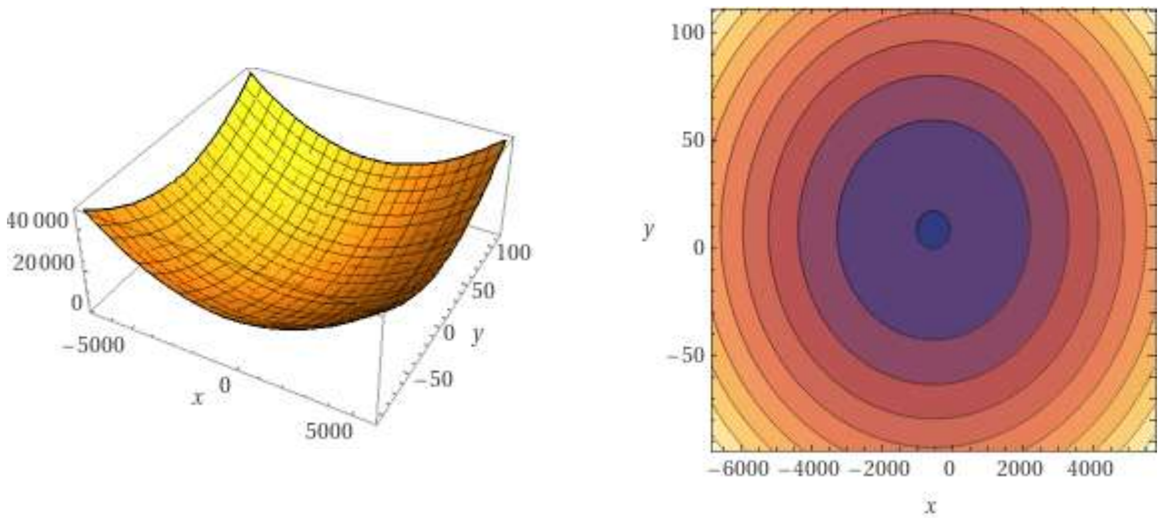
$$TF = ax^2 + by^2 + cx + dy + exy + f \quad (4)$$

where: TF – Technical fiber (%); x, y – biometric parameters of elite plants considered in the study (Table 4); a, b, c, d, e, f – the coefficients of the equation (4); all values are presented in Table 4.

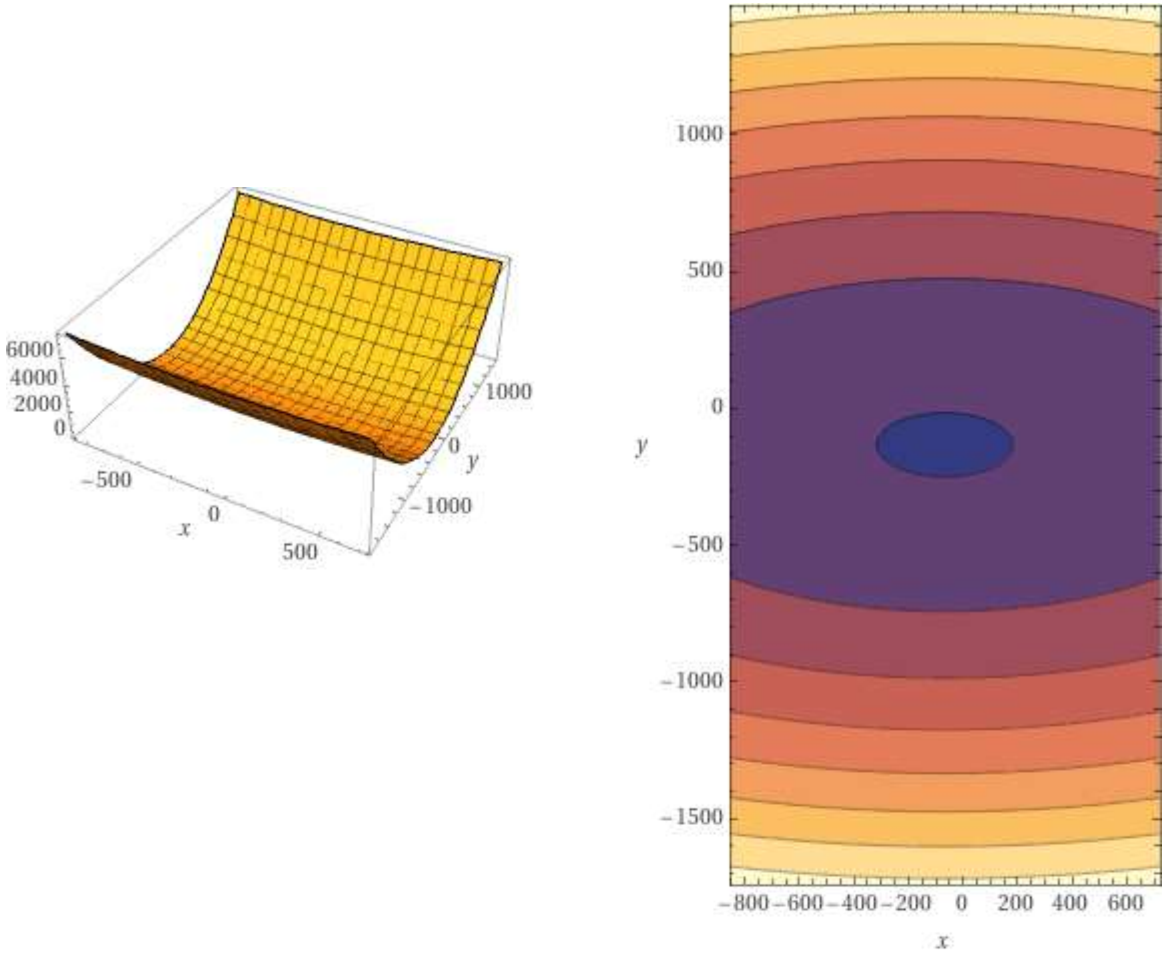
Table 4. Values of the equation (4) coefficients for the description of the TF index variation in industrial hemp

Biometric parameters	The coefficients of the Eq. (4)						Statistical safety parameters		
	a	b	c	D	e	f	R^2	p	RMSEP
x=TPW y=MSD	0.000687	1.960412	0.721412	-33.725505	-0.085277	178.396379	0.636	0.019*	2.1733
x=SL y=TL	-0.002685	-0.000479	0.829316	-0.530436	0.002876	-26.805030	0.189	0.728	3.2444
x=TL y=MSD	-0.000208	-0.161210	0.445861	6.635047	-0.028764	-37.346792	0.370	0.288	2.8593
x=TPW y=DSW	0.006221	0.077195	-0.263348	1.597033	-0.048093	28.255546	0.550	0.058	2.3169
x=TL y=DSW	0.000613	0.002797	0.080341	0.750581	-0.008263	14.387326	0.595	0.034*	2.2925
x=MSD y=DSW	3.483541	0.076379	-51.517695	8.283841	-1.087770	219.070596	0.644	0.017*	2.1509
x=SL y=DFC	-0.002720	-2.591058	0.333292	-15.603287	0.179304	34.946019	0.199	0.703	3.2247
x=TL y=DFC	-0.001376	-1.215268	-0.202063	-2.166022	0.101856	57.147587	0.240	0.596	3.1413

* p <0.05
Source: Original data resulted by calculations.

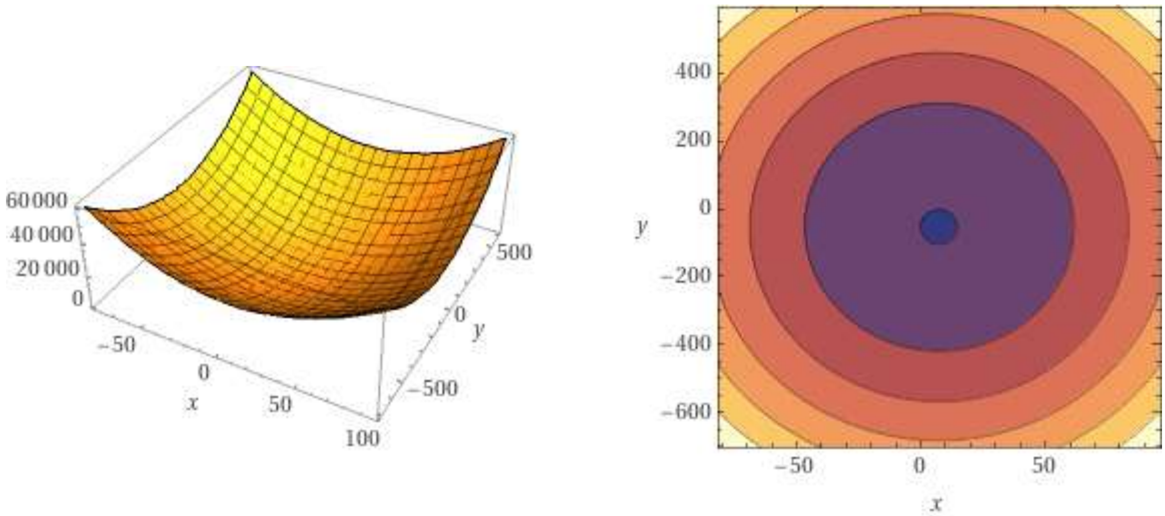


(a) (b)
Fig. 2. Graphic distribution of TF in relation to TPW (x-axis), and MSD (y-axis), industrial hemp
Source: Original graphs.



(a) (b)

Fig. 3. Graphic distribution of TF in relation to TL (x-axis), and DSW (y-axis), industrial hemp
Source: Original graphs.



(a) (b)

Fig. 4. Graphic distribution of TF in relation to MSD (x-axis), and DSW (y-axis), industrial hemp
Source: Original graphs.

In order to evaluate the differences regarding the technical fiber (TF), the comparative analysis was applied to the three genotypes, respectively Teodora and Lv-300 in relation to Silvana, considered as the control variant. From the comparative analysis of the Teodora genotype in relation to Silvana (control variant), average values of TF_S=28.388

(Silvana) and TF_T=31.355 (Teodora) resulted. According to the t-test, the result was t=2.5948, with p=0.013 ($p<0.05$). The recorded results (t, p values) rejected the null hypothesis; therefore there are significant differences, with statistical assurance, between the two genotypes (Teodora compared to Silvana, as a control variant). Additional verification of the differences between the two genotypes was done based on the non-parametric Mann-Whitney test. The value U=72 (p=0.0045), also indicated significant differences between the data series for the TF productivity index in the two genotypes, Teodora in relation to Silvana.

The Lv-300 genotype was also analyzed compared to the Silvana genotype (as control variant). From the comparative analysis of the Lv-300 genotype in relation to Silvana (control), average values of TF_S=28.388 (Silvana) and $TF_{Lv\text{-}300}$=29.357 (Lv-300) resulted. According to the t-test, the result was t=0.763, with p=0.451 ($p>0.05$). The recorded results (t, p values) showed that there are differences between the two genotypes, but without statistical assurance ($p>0.05$) (Lv-300 compared to Silvana, as the control variant). Additional verification of the differences between the two genotypes was done based on the non-parametric Mann-Whitney test. The value U=117 (p=0.158), also indicated differences between the two genotypes, but without statistical certainty ($p>0.05$).

Industrial hemp has a high agronomic and economic importance, and reaches the time of harvest in optimal crop conditions, after a period of 90-120 days [4].

Due to the biological specificity of the plants and the high biomass productions achieved, industrial hemp has high soil requirements; it requires soils with a neutral pH (weakly acid, weakly alkaline, pH=6.0 - 7.5), well-drained soils, with a good water regime, moist, soils with a well-represented profile [10].

The industrial hemp crop is a crop of interest for the objectives of the European Green Pact, with a number of benefits for the environment. Thus, hemp crop contributes during the vegetation period (approx. 5 months) to carbon fixation (9-15 t CO_2 ha^{-1}), a similar amount of carbon fixed by a young forest, but the hemp crop in a much shorter period of time. From an agronomic point of view, the hemp crop contributes to interrupting the cycle of some pathogens (diseases) with benefits in crop rotation, and also contributes to reducing the degree of soil pollution (great shading capacity). It contributes to the reduction of soil erosion, to the regulation of the water regime in the soil. It also has an important role in biodiversity, through the flowering period (July - September) and the large amount of pollen it produces, a period that is otherwise scarce for pollinating species and bees. It provides shelter for some species of birds (large habitat of the crops and plants, height of 2.5 - 4.5 m), as well as the source of food through seeds. It can also be considered an "environmentally friendly" plant, due to the reduced need for pesticides in the crop technology [5]. The products (fiber, seeds) and by-products (leaves, stems, roots, ingot-cellulose) resulting from the culture of industrial hemp, show high potential, with a wide spectrum of valorisation in the textile industry (fiber production), the food industry and animal husbandry (hemp seeds), constructions industry (hemp fiber, ingot-cellulosic mass), pulp and paper industry (fiber, ingot-cellulosic mass), other directions and industry of use (cosmetics, bioenergy production, composite material, etc.).

Industrial hemp (*Cannabis sativa* L.) is grown for industrial use, and the EU catalog includes 75 varieties. According to international legislation and EU Regulation 1308/2013 (Art. 189) [6], industrial hemp must fall under NC code 5302 10 (THC<0.3%), as well as other legal provisions regarding the cultivation of this plant for industrial purposes [5].

Farmers growing industrial hemp, according to EU rules, are eligible for direct payments on the area cultivated with industrial hemp under the CAP, and also, under certain conditions, they can benefit from voluntary coupled support (VCS) (support currently implemented in three countries, France, Poland, and Romania) [5].

The present study contributes through the results presented to the database and information regarding industrial hemp, with the comparative presentation of the three varieties analyzed, and the results regarding the fiber productivity elements in relation to the physiological parameters and indices of the elite plants.

CONCLUSIONS

The study facilitated the comparative evaluation of the three genotypes of industrial hemp, under the aspect of fiber productivity elements in relation to biometric and physiological plant parameters and indices.

Various levels of correlations were recorded between fiber productivity elements (dry fiber content – DFC, pure fiber weight – PFW), and technical fiber – TF), and plant physiological parameters and indices, an important aspect for hemp breeding programs industrial, but also for cultural technologies.

Models in the form of equations, as well as graphical models, described the variation of the fiber productivity elements (DFC, PFW, TF) in relation to parameters and physiological indices of the elite plants, under statistical safety conditions in the case of some parameters and combinations (DSW, MSD, NSD, TL, and TPW).

The comparative analysis of the varieties Teodora and Lv-300 with Silvana (as control genotype) highlighted differences in the technical fiber (TF), in the study conditions, with statistical assurance in the case of Teodora, which represents a perspective genotype.

The recorded results are important for industrial hemp breeding programs, but also for crop technologies, with the aim of yields of quality fiber productivity.

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